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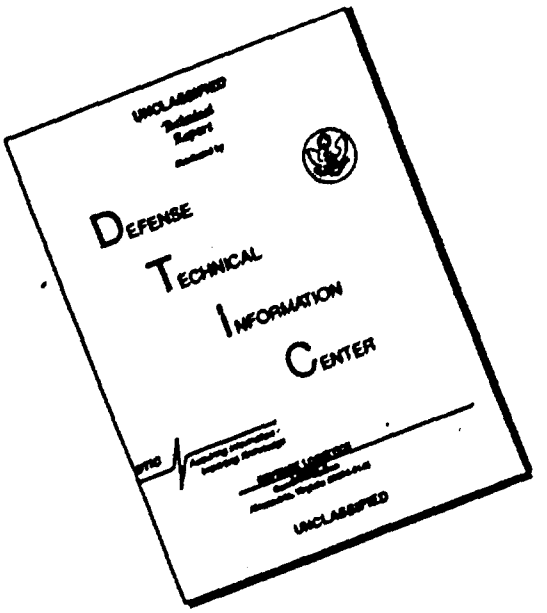

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OTS PB 171421

DMIC Report 152
April 28, 1961

BINARY AND TERNARY PHASE DIAGRAMS
OF
COLUMBIUM, MOLYBDENUM, TANTALUM, AND TUNGSTEN

DEFENSE METALS INFORMATION CENTER
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1. To collect, store, and disseminate technical information on the current status of research and development of the above materials.

2. To supplement established Service activities in providing technical advisory services to producers, melters, and fabricators of the above materials, and to designers and fabricators of military equipment containing these materials.

3. To assist the Government agencies and their contractors in developing technical data required for preparation of specifications for the above materials.

4. On assignment, to conduct surveys or laboratory research investigations, mainly of a short-range nature, as required, to ascertain causes of troubles encountered by fabricators, or to fill minor gaps in established research programs.

Contract No. AF 33(616)-7747

OTS PB 171421

DMIC Report 152
April 28, 1961

BINARY AND TERNARY PHASE DIAGRAMS OF COLUMBIUM, MOLYBDENUM, TANTALUM, AND TUNGSTEN

by

J. J. English

to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

PREFACE

The following references were used extensively in compiling this report on refractory-metal phase diagrams:

(1) Constitution of Binary Alloys, by M. Hansen and K. Anderko

(2) Tantalum and Niobium, by G. Miller

(3) Tantalum and Tantalum Alloys, DMIC Report 133, by F. F. Schmidt

(4) Physical and Mechanical Properties of Columbium and Columbium-Base Alloys, DMIC Report 135, by E. S. Bartlett and J. A. Houck

(5) A Study of Ternary Phase Diagrams of Tungsten and Tantalum, by W. Rostoker

(6) Molybdenum Metal Technical Notes – Constitution Diagrams, by R. R. Freeman and J. Z. Briggs

(7) Tungsten – Bibliography, 1953-1958, by P. W. Felten

These references were supplemented by library research and by interviews with Government contractors now conducting work in this field.

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BINARY AND TERNARY PHASE DIAGRAMS OF COLUMBIUM, MOLYBDENUM, TANTALUM, AND TUNGSTEN

SUMMARY

This report contains a compilation or discussion of 93 binary and 68 ternary phase diagrams of the four refractory metals, columbium, molybdenum, tantalum, and tungsten. Included with each diagram is a discussion which lists information on the solubility and crystal structure of intermediate phases. When several investigations of a particular diagram are in disagreement, the discrepancies are discussed.

Many of the diagrams are incomplete, and are subject to revision as more definitive data become available. However, they are included in this report so that the readers may have as up-to-date information as possible on each of the systems.

INTRODUCTION

Because of the need for structural materials for use at higher and higher temperatures, much research and development emphasis has been placed on the refractory metals columbium, molybdenum, tantalum and tungsten. These four metals have the highest melting points and highest strength at high temperatures of all the metallic elements available in useful quantities. The emphasis in research and development activities has been on alloy development, physical metallurgy, oxidation behavior, protective-coating systems, and melting and fabrication methods. In almost all of these activities a knowledge of the alloying behavior as exemplified by the phase diagram is important.

This report consists of a compilation of the phase diagrams for alloys of columbium, molybdenum, tantalum, and tungsten. Many of the diagrams are not complete, while others are subject to revision as more definitive data become available. It is hoped that users of this report will supply DMIC with any additional phase-diagram information on these metals that is, or may become, available.

ORGANIZATION OF THE REPORT

The phase diagrams in this report are divided into two sections: binary systems and ternary systems. The binary diagrams are arranged into four groups, one for each of the four metals. Within each group the systems are arranged in alphabetical order according to the spelling of the second element in the system. A diagram involving two of the four subject metals is listed only in the first alphabetical grouping. For example, the columbium-molybdenum system is not repeated as the molybdenum-columbium system.

The ternary phase diagrams are also arranged alphabetically in four groups. When two or more refractory metals occur in a system they are listed first, in alphabetical order. For example, the columbium-tantalum-chromium system will not be listed as the columbium-chromium-tantalum system.

This report has been bound with a plastic binder. This will permit additional diagrams to be added as they become available. If desired, the diagrams can be removed from the present binder and inserted in an appropriate loose-leaf binder.

THE PHASE DIAGRAMS

The four refractory metals, whose phase diagrams are compiled in this report, have body-centered cubic structures. Columbium and tantalum are Group V-A elements and molybdenum and tungsten are Group VI-A elements. The melting points and lattice constants of each of the four elements are listed below:

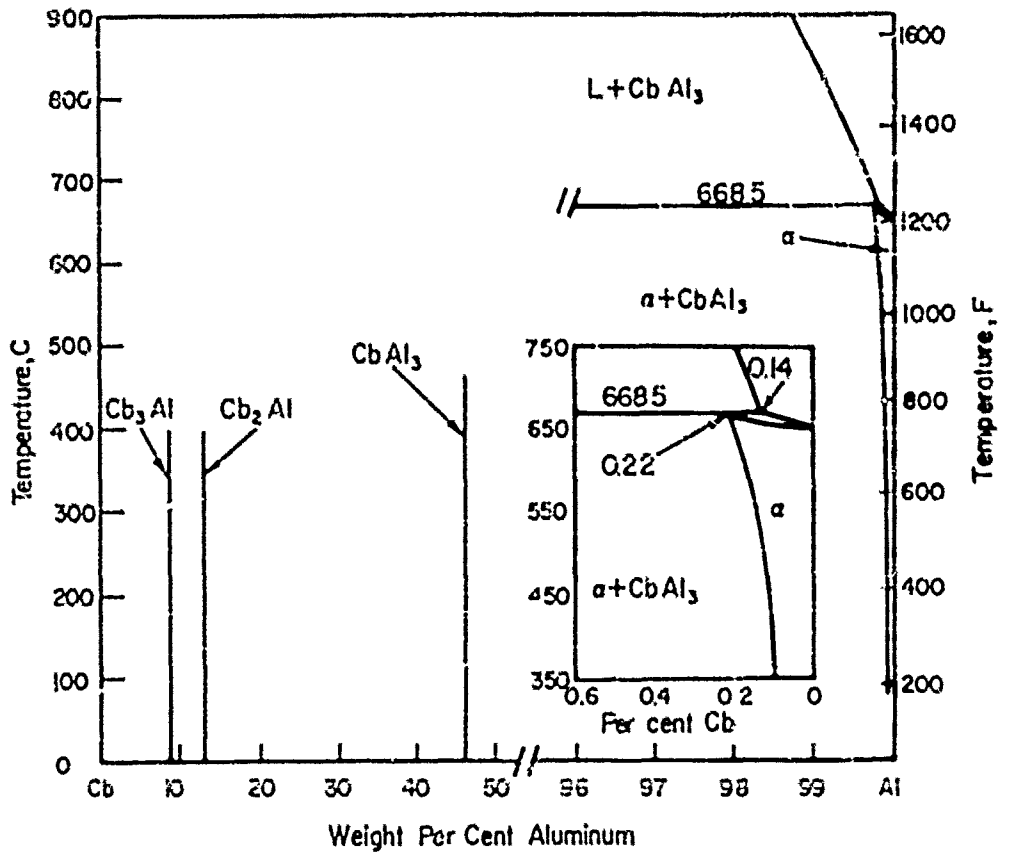
	Melting Point		Lattice Parameter, A
	C	F	
Columbium	2460	4460	3.300
Molybdenum	2620	4750	3.147
Tantalum	2996	5430	3.303
Tungsten	3410	6170	3.165

As would be expected from their lattice constants, these elements are mutually soluble in one another. However, the phase diagrams with other systems vary considerably from one base to another. For example, columbium and tantalum have high solubilities for interstitial elements while molybdenum and tungsten do not.

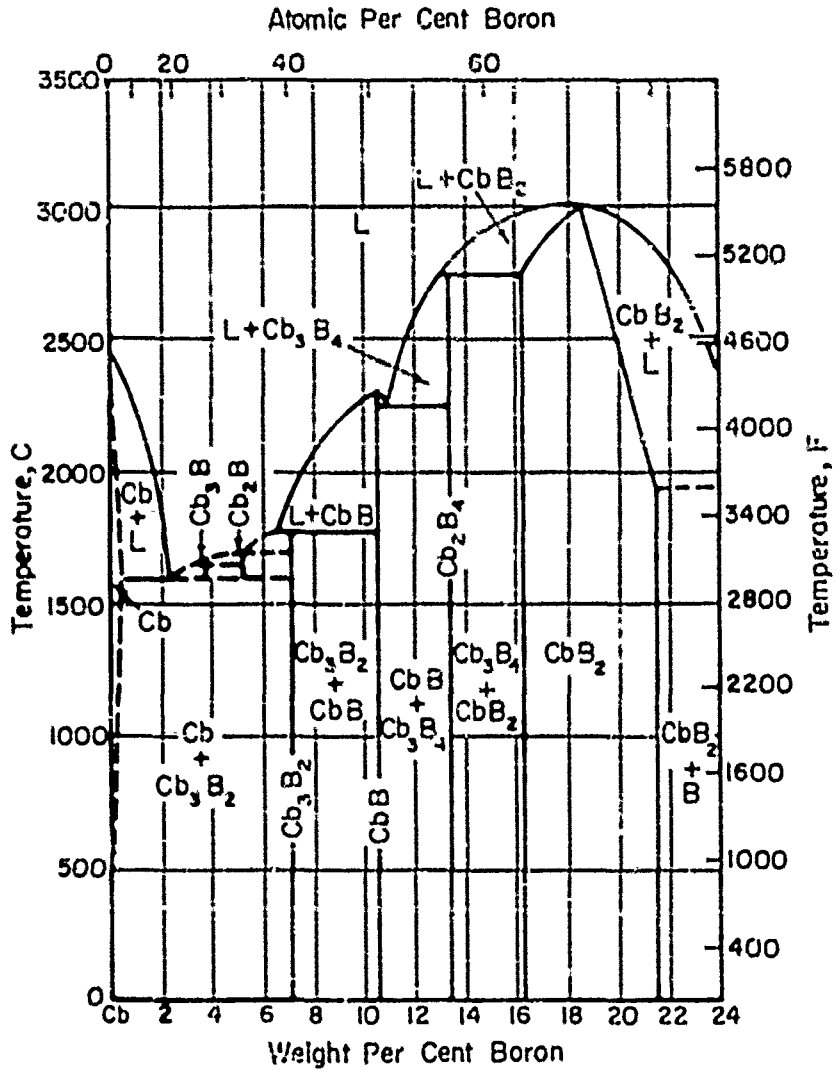
In the phase diagrams which follow, a short discussion is included below each diagram. It lists information such as maximum solubility and the crystal structure of intermediate phases. When several investigations of a particular diagram are in disagreement, the discrepancies are discussed.

In the discussions the numbers in parentheses refer to references listed in the Bibliography at the end of the report.

BINARY PHASE DIAGRAMS

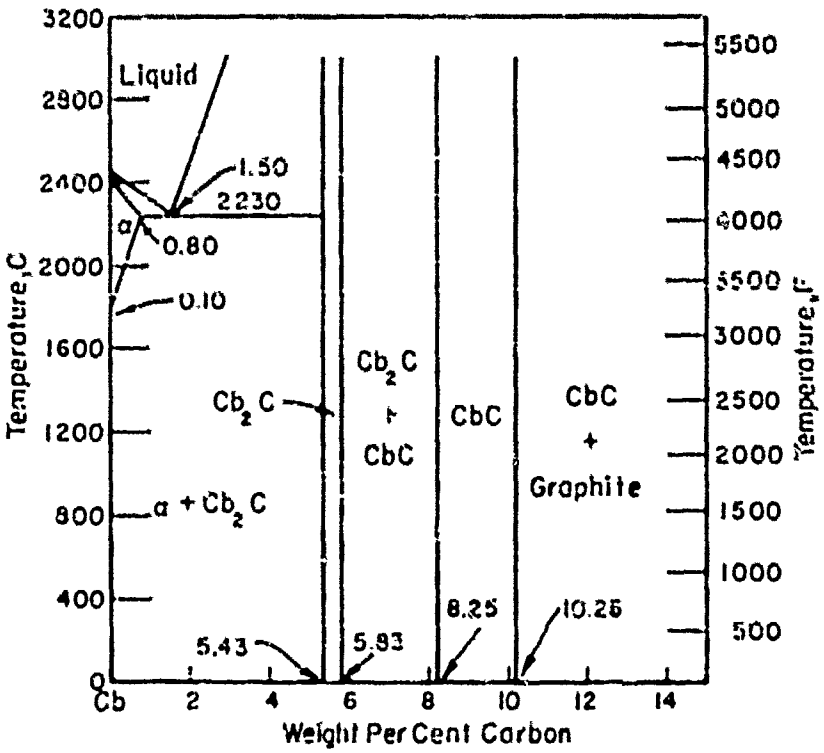


Three intermediate phases have been reported. Cb_3Al has a cubic, beta-tungsten structure with a = 5.187 A.(1) Cb_2Al has a tetragonal, sigma-type structure with a = 9.943 A, c = 5.128 A, and c/a = 0.522.(2) $CbAl_3$ is tetragonal with a = 5.498 A, c = 8.601 A, and c/a = 1.582.(3)



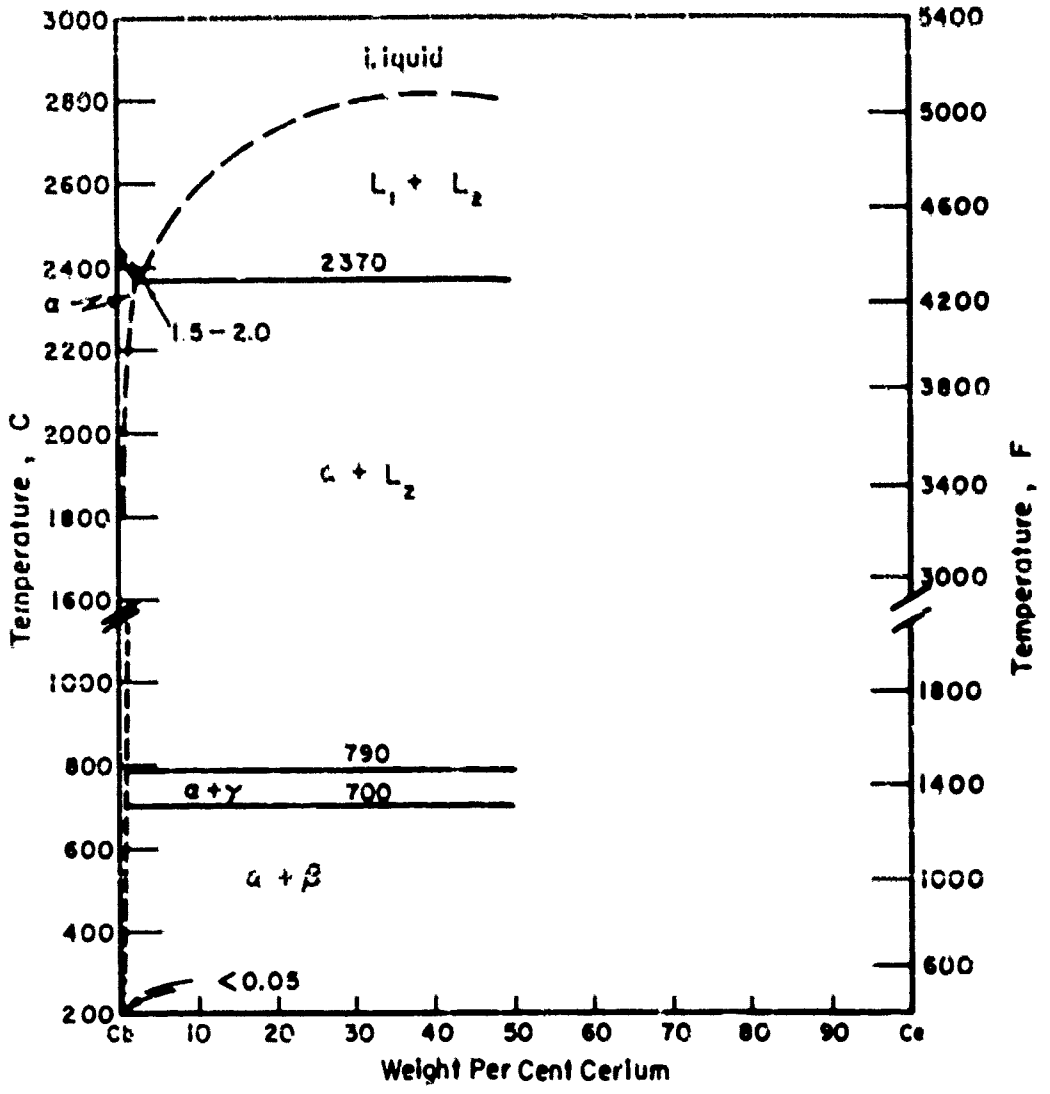
Cb_3B_2 has a tetragonal, U_3Si_2-type structure with a = 6.173 kX, and c = 3.214 kX.[4] CbB is an orthorhombic, CrB-type structure with a = 3.298 A, b = 8.724 A, and c = 3.166 A.[5, 6] Cb_3B_4 is an orthorhombic, Mn_3B_4-type structure with a = 3.295 A, b = 14.05 A, and c = 3.137 A.[6] CbB_2 is a hexagonal, C32-type structure with a = 3.089 A, c = 3.303 A, and [illegible].[6, 7] Cb_3B and Cb_2B also exist over limited temperature ranges.[5, 6] The solubility of boron [illegible] is less than 0.005 weight per cent at 1500 C.[168]

COLUMBIUM-CARBON SYSTEM

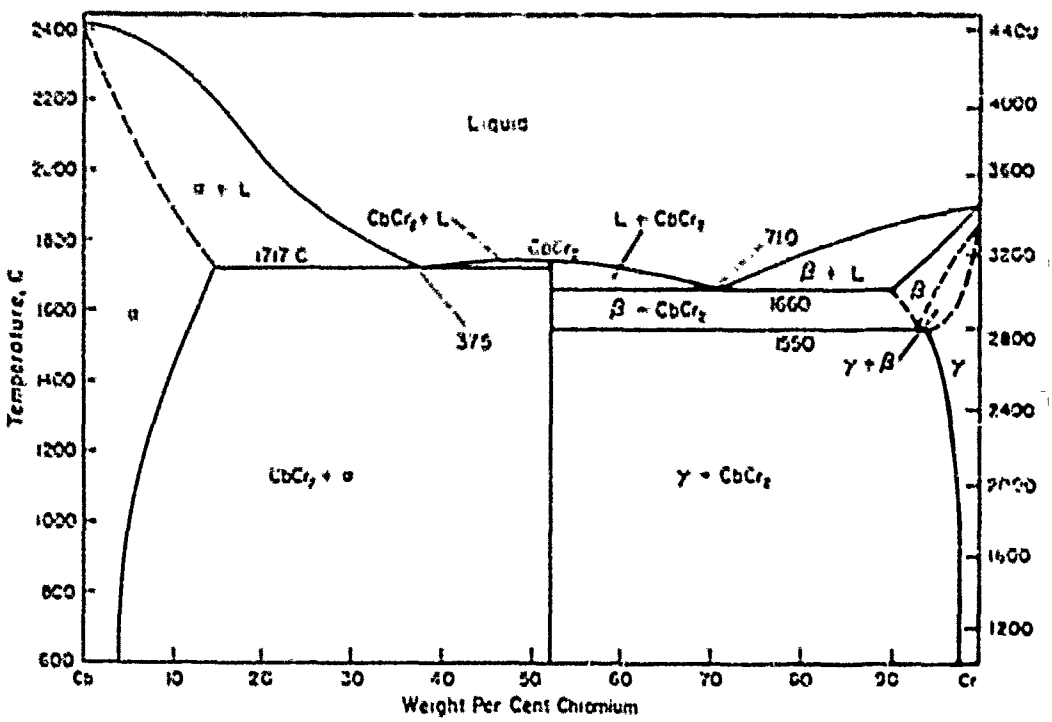


Two carbides of columbium exist. Cb_2C is hexagonal, having a limited region of solubility between 5.43 and 5.83 weight per cent carbon. CbC is a face-centered cubic with a lattice parameter $a = 4.470$ A.[8, 9] Metallographic evidence indicates the existence of a peritectic reaction $L + CbC \rightarrow Cb_2C$ at some undetermined temperature. Alloys richer in carbon than the CbC phase freeze by the eutectic reaction $L \rightarrow CbC$ + graphite at approximately 3250 C.[10]

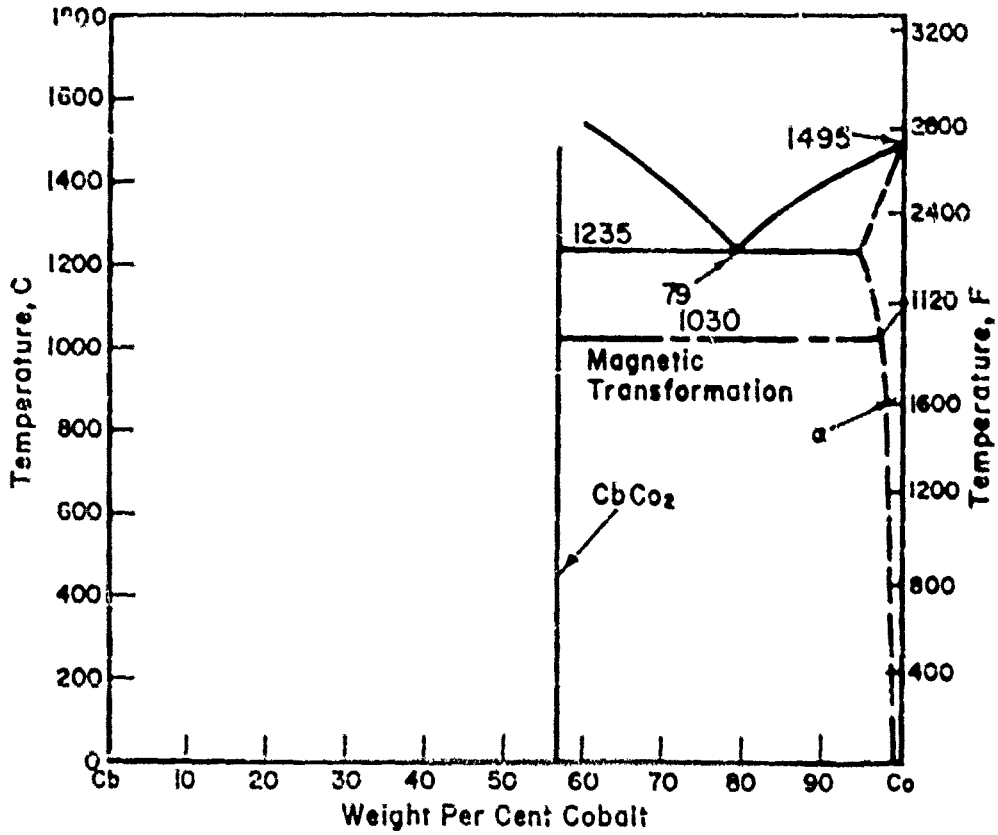
COLUMBIUM-CERIUM SYSTEM



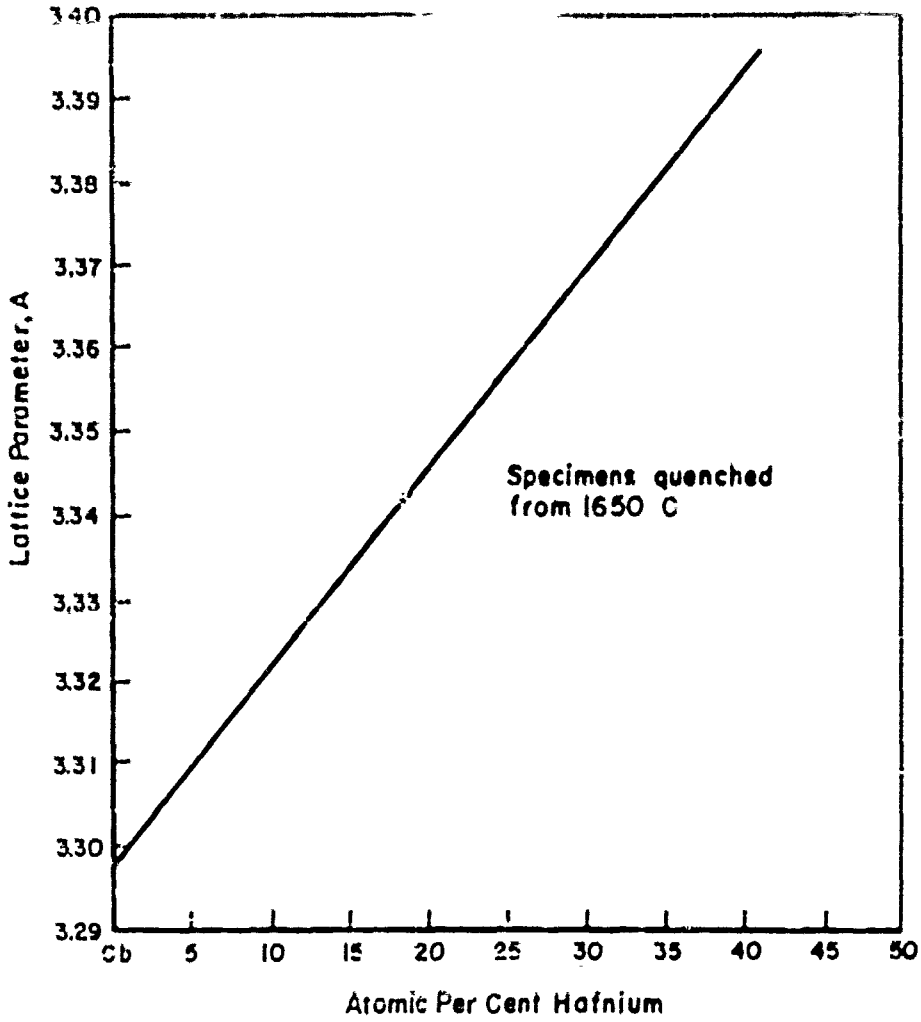
The phase diagram shows an extensive region of immiscibility in both the liquid and the solid states. The monotectic horizontal lies at 2370 ± 20 C. The melting temperature was reduced from 2415 C for pure columbium to 2360-2380 C with 0.2 weight per cent cerium. Separation into two liquid layers starts at 1.0 to 2.0 weight per cent cerium.(11)



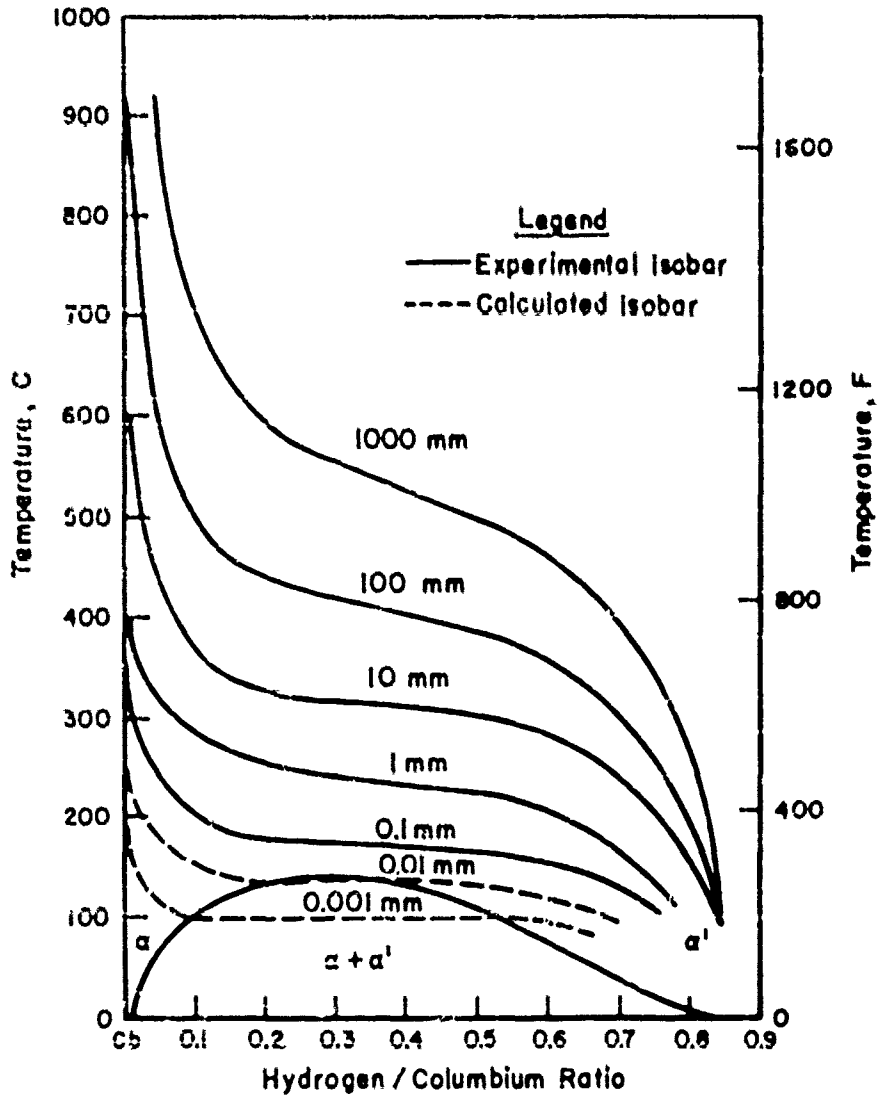
The solubility of chromium in columbium is approximately 12 weight per cent at 1500 C, decreasing to 4 weight per cent at 800 C. The solubility of columbium in chromium is 5 weight per cent at 1500 C, decreasing to 2 weight per cent at 800 C.(12) $CbCr_2$ is face-centered cubic with a = 6.95-6.97 kX.(13)



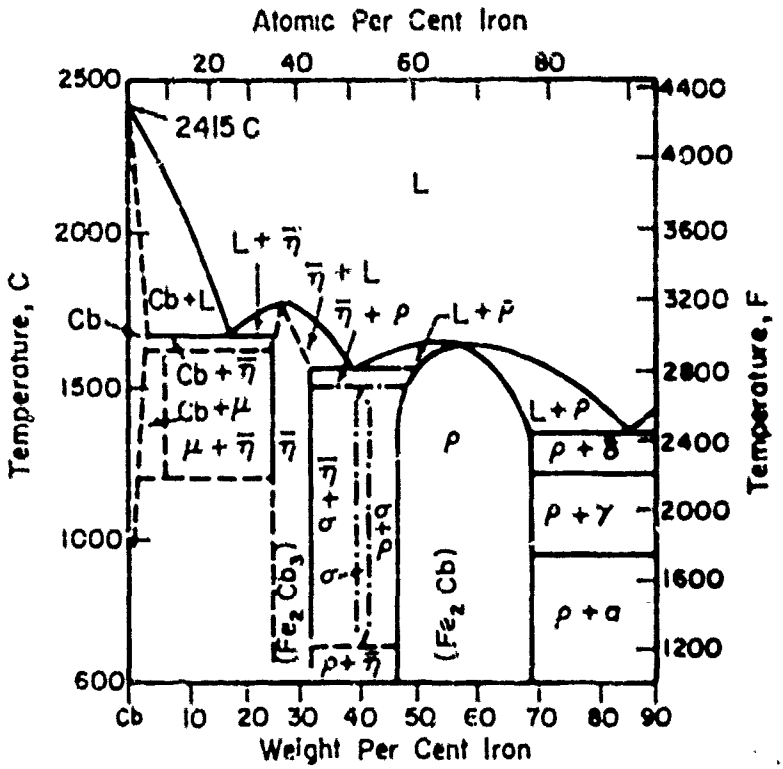
$CbCo_2$ is believed to exist in two modifications. One is at 33.3 atomic per cent columbium having a cubic $MgCu_2$(C15) type of structure with a = 6.758 A. The second structure exists around 27 atomic per cent and is the $MgNi_2$(C36) type of structure. The lattice spacings for this structure were reported as a = 4.735 A, c = 15.46 A, and c/a = 1.631.(14, 15, 16)



The solubility of hafnium in columbium is expected to be greater than 40 atomic per cent (49 weight per cent) at 1650 C.(169)

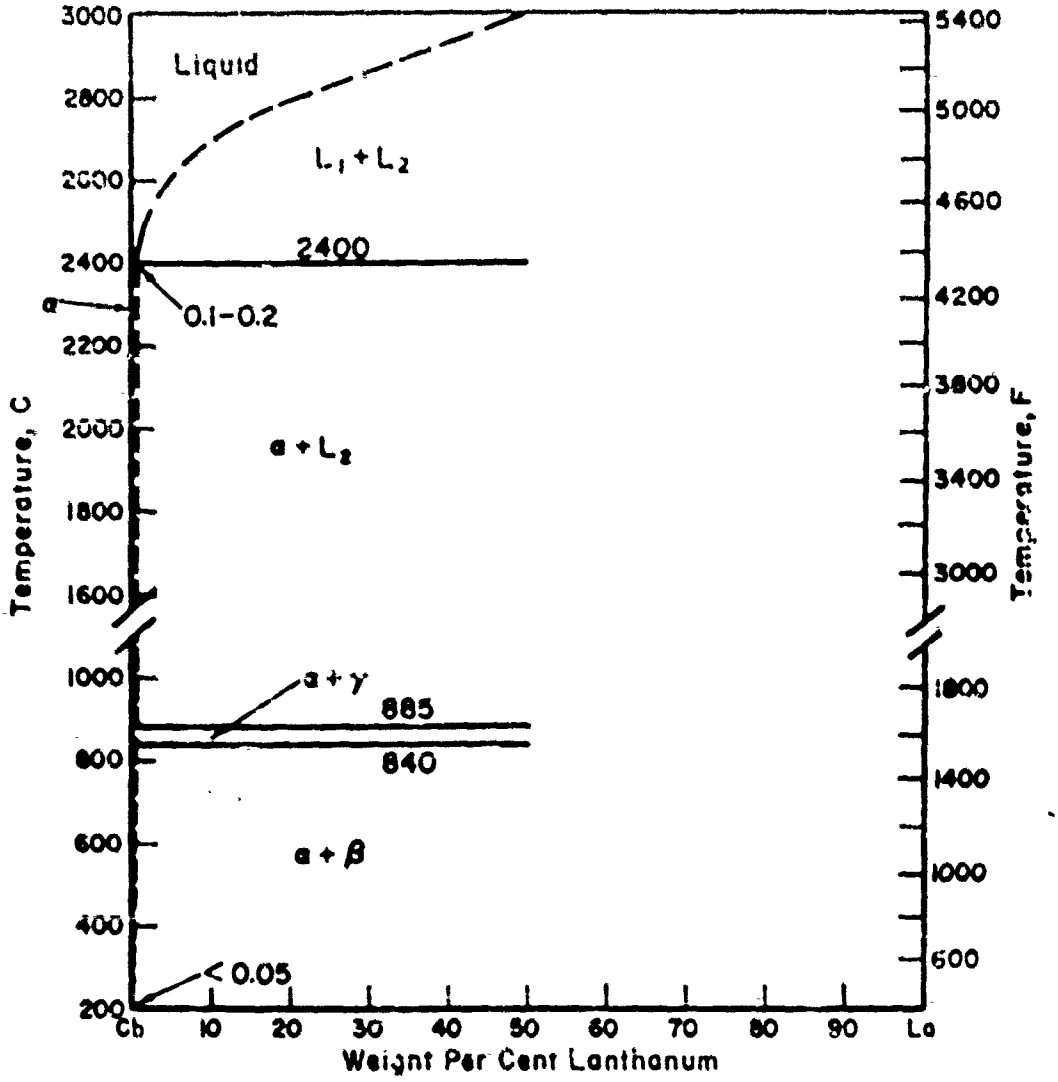


Equilibria and X-ray studies show that in the ranges 100 to 900 C, 0.1 to 1000 mm Hg pressure, and 0.01 to 0.85 H/Cb ratio, the columbium-hydrogen system consists of a single-phase body-centered cubic structure. A two-phase region is present at relatively low temperatures and pressures with the critical point located at 140 C, 0.01 mm of Hg pressure, and 0.3 H/Cb ratio.(18)

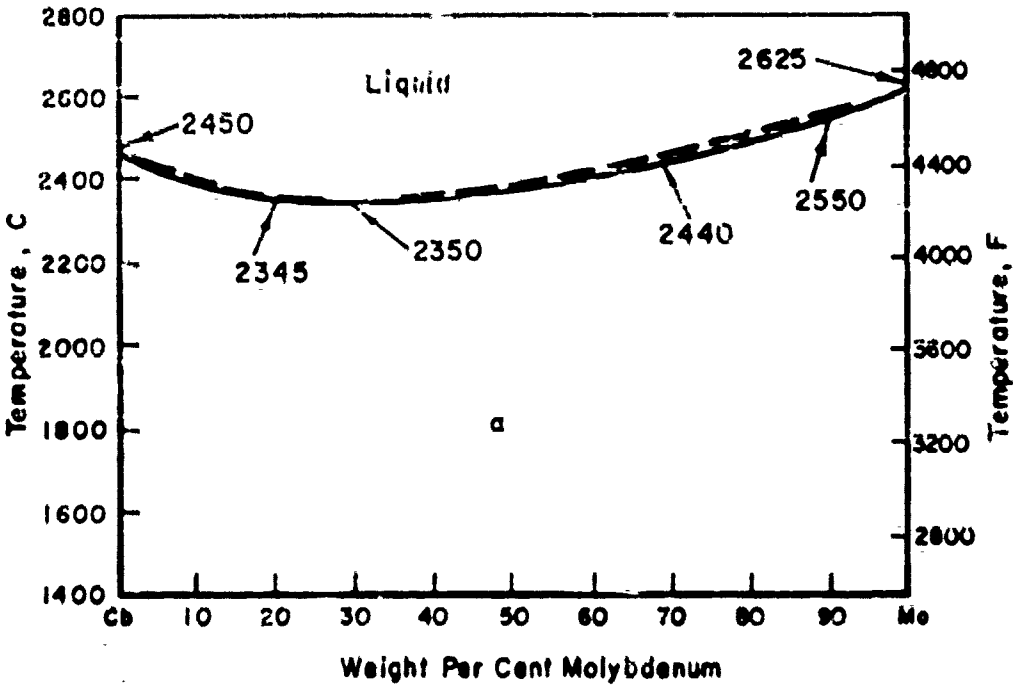


The phase diagram prepared by Goldschmidt shows a high-temperature σ-phase similar to other transition-metal systems. Fe_2Cb_3 is an η-carbide-type structure with a = 11.239 Å.[17] Fe_2Cb is isotypic with $MgZn_2$ with a = 4.830 Å, c = 7.822 Å, and c/a = 1.632.[14] The terminal solid solutions of columbium in iron and of iron in columbium are small and decrease with decreasing temperature.

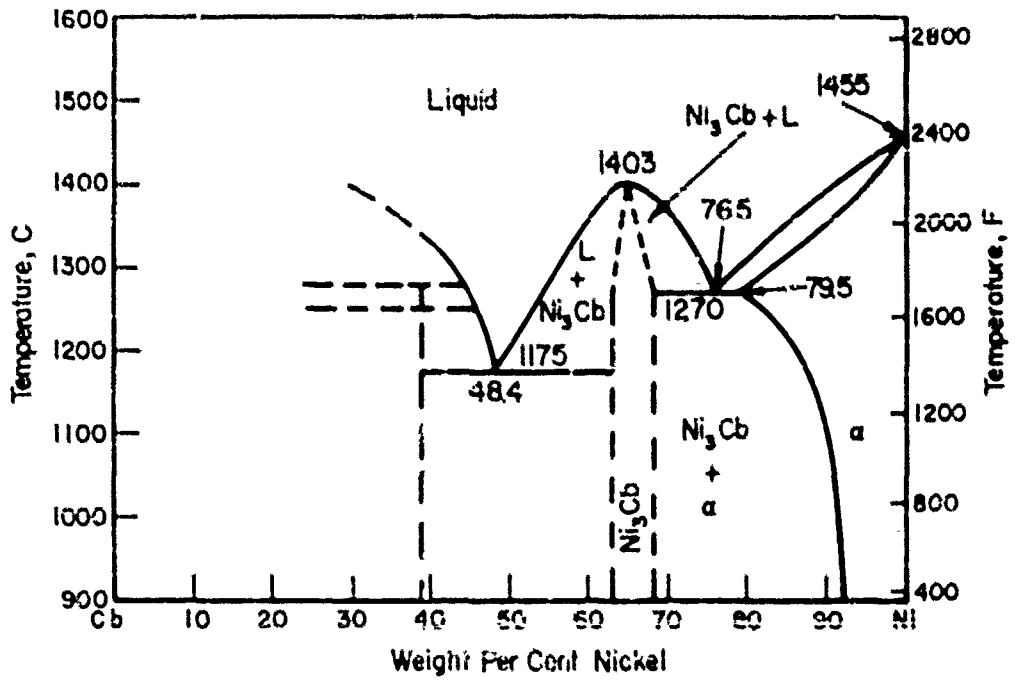
COLUMBIUM-LANTHANUM SYSTEM



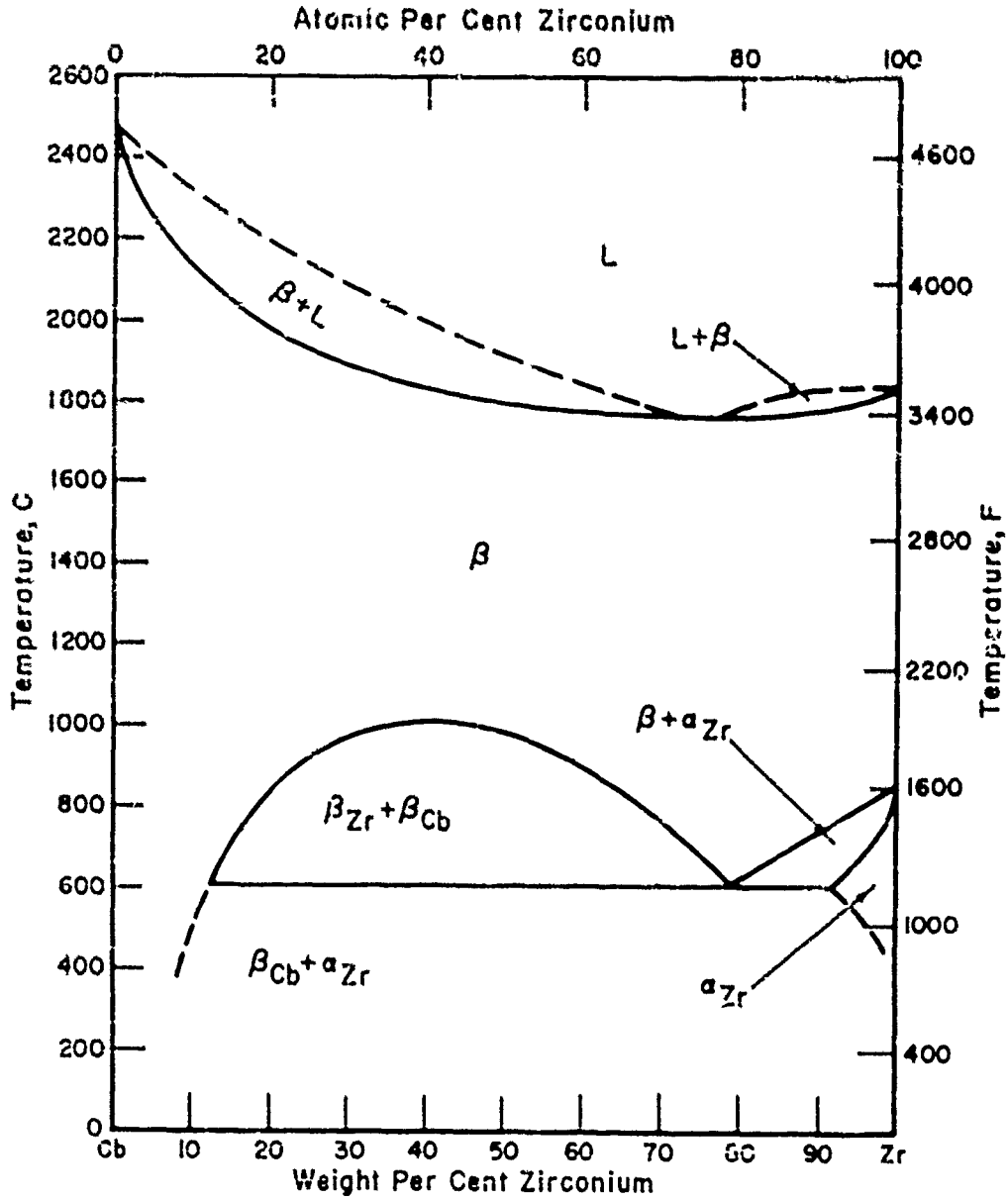
Extensive regions of immiscibility occur in the liquid and the solid regions. The monotectic horizontal lies at 2400 ± 20 C. Separation into two layers occurs at 0.1 to 0.2 weight per cent lanthanum. The solubility in the solid state is less than 0.05 weight per cent at room temperature.[11]



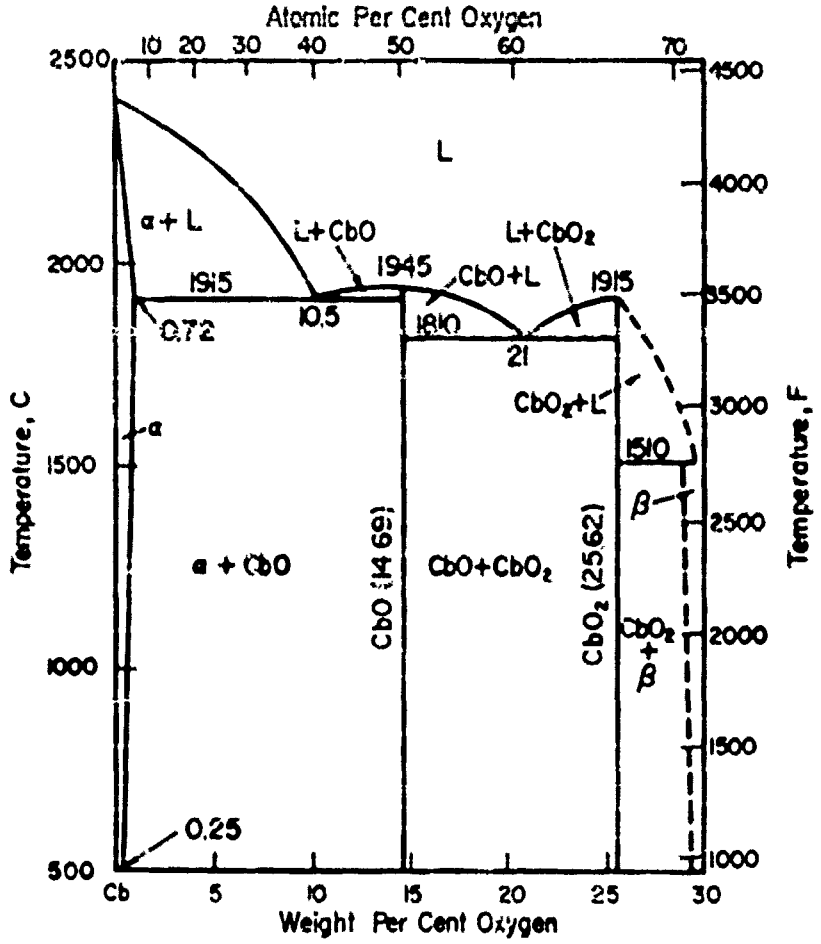
Columbium and molybdenum form a continuous series of solid solutions.[19] Kornelov determined the melting point of alloys containing 20, 30, 70, and 90 weight per cent molybdenum.[20]



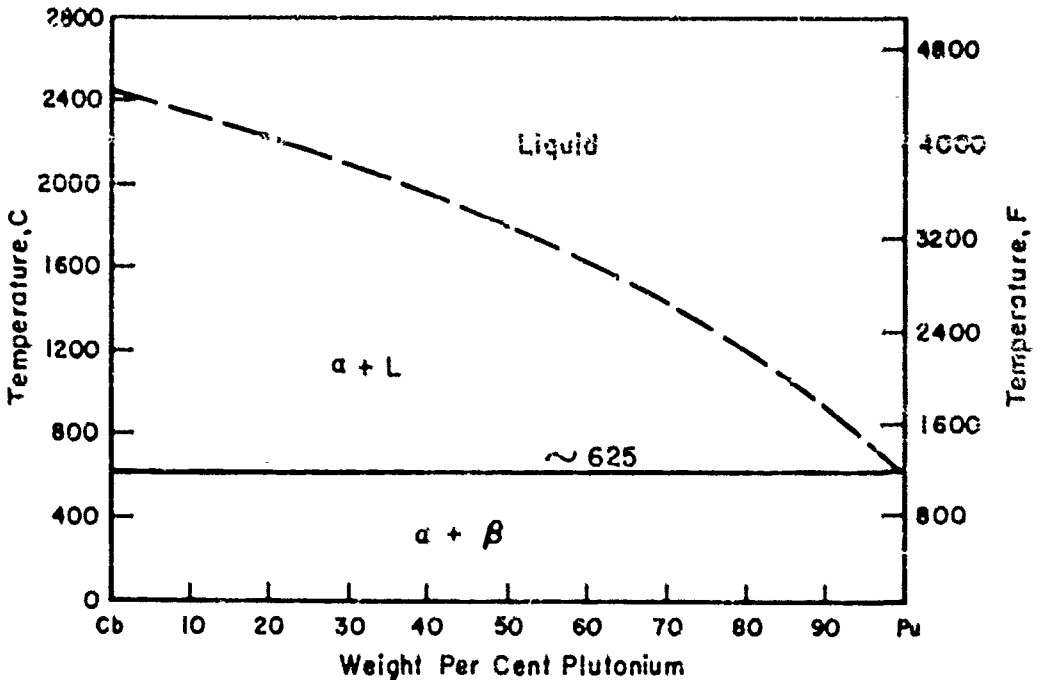
CbNi3 has an orthorhombic TiCu3-type structure with lattice parameters: a = 5.10 kX, b = 4.55 kX, and c = 4.25 kX.(23) The solubility of columbium in nickel is approximately 15 weight per cent at 1250 C. The solubility of nickel in columbium is less than 5 weight per cent.(24) The diagram was constructed from the data prepared by Rogodin and Selektmann.(25)



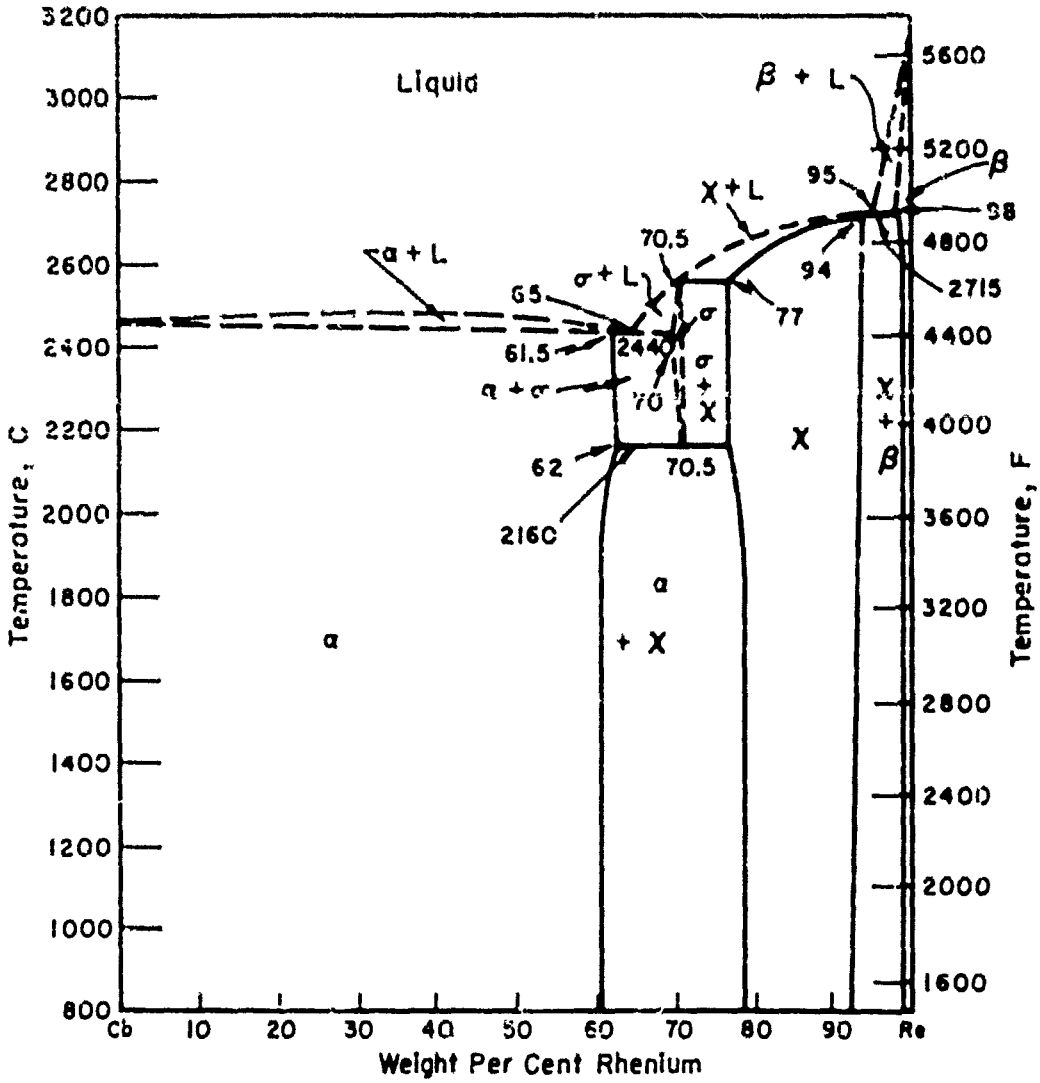
The diagram developed by Rogers and Atkins shows that complete solid solubility exists above 1000 C.[53] A eutectoid occurs at approximately 625 C and 32.5 weight per cent zirconium. The horizontal extends from 13 to 93.5 per cent zirconium. Domagala placed the eutectoid temperature at 800 C, with the continuous series of solid solutions existing above 1180 C.[54]



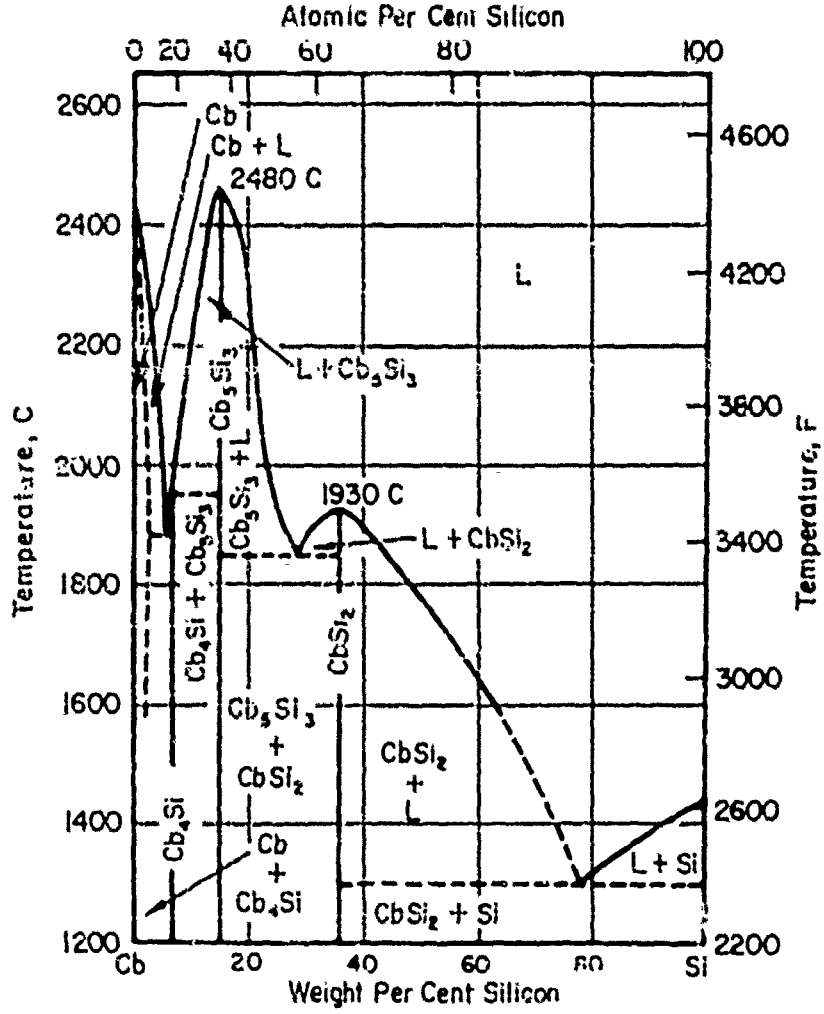
Brauer reported that three oxides of columbium exist with limited regions of homogeneity. CbO possesses a cubic structure with $a = 4.211$ A and six atoms per unit cell (NaCl lattice with ordered vacancies). The CbO_2 structure is similar to the rutile structure.[26] Cb_2O_5 occurs as three crystalline modifications.[27] The solid solubility of oxygen in columbium varies from 0.25 weight per cent at 500 C to 0.72 weight per cent at the eutectic temperature 1915 C.[28]



It is believed that no intermediate phases exist in this system.[29]

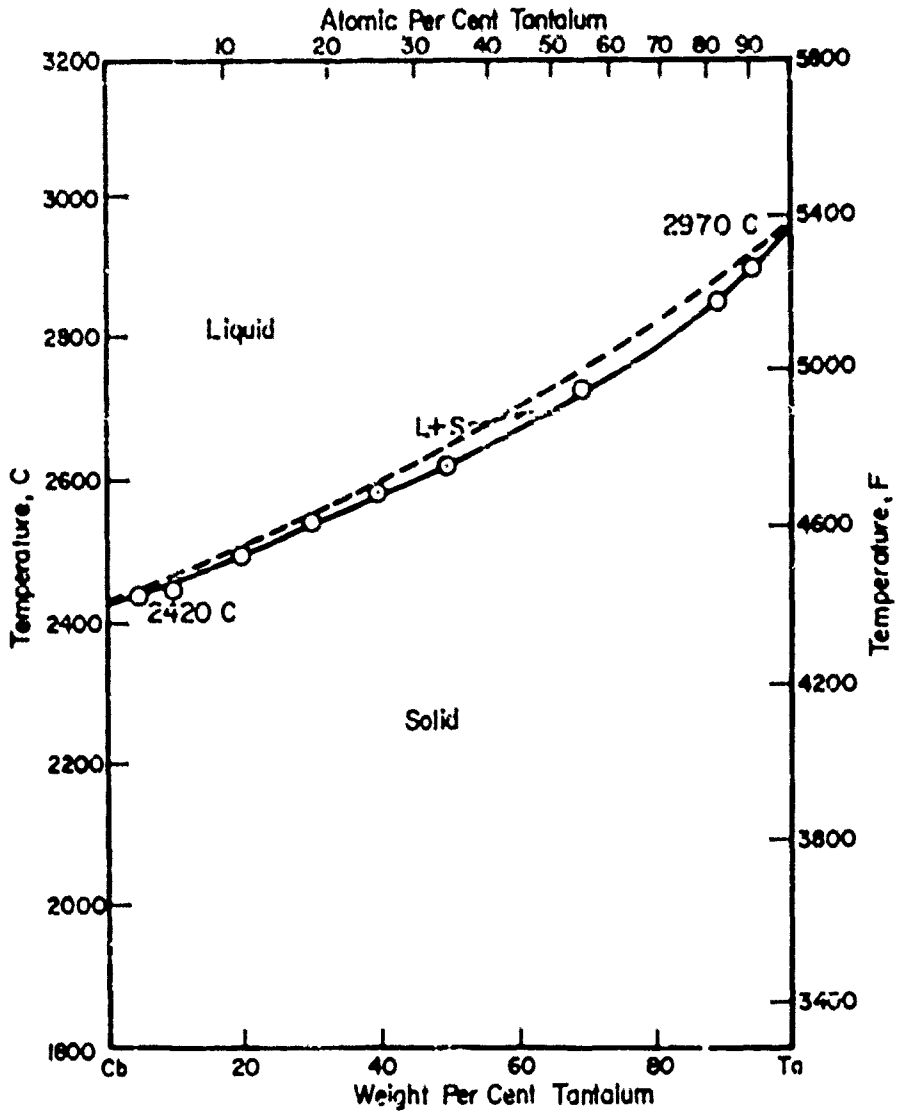


Two compounds are present in this system. The sigma phase is isomorphous with iron-chromium sigma with a = 9.72 A, c = 5.07 A, and c/a = 0.52.[30] The chi phase is an α-Mn-type structure with a = 9.87 A.[31] The diagram shown is the result of work performed by Grant and Giessen.[32] It differs from prior work in the stability range for the sigma phase. Greenfield and Beck[30] and Levesque, Bekebrede, and Brown[33] state that the sigma phase is stable only in the temperature range below 1075 C. Knapton's hypothesis that sigma is stable at high temperatures[34] agrees with Grant's results.



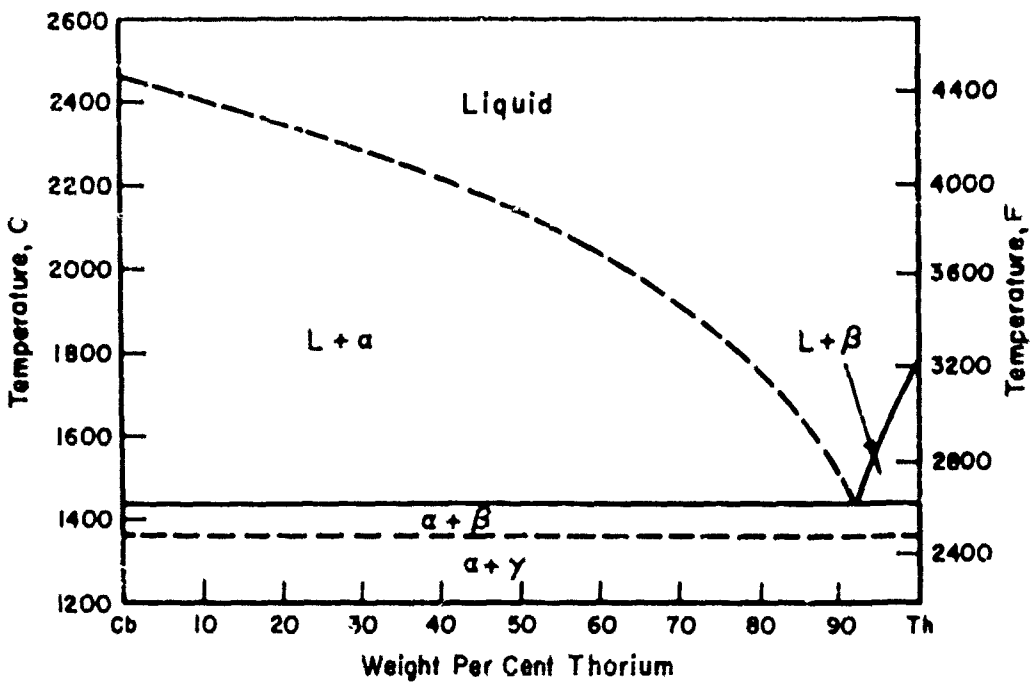
Three intermediate phases were reported by Knapton.[35] Cb_5Si is isomorphous with Ta_4Si and Zr_4Si. Samsonov reported the structure to have a hexagonal ϵ-Fe_3N-type structure with a = 3.59 A and c = 4.46 A.[36] Cb_5Si_3 exists in two modifications, with the transformation between 1900 and 2100 C.[35] $CbSi_2$ has a hexagonal $CrSi_2$-type structure with a = 4.795 A, c = 6.589 A, and c/a = 1.374.[37]

COLUMBIUM-TANTALUM SYSTEM



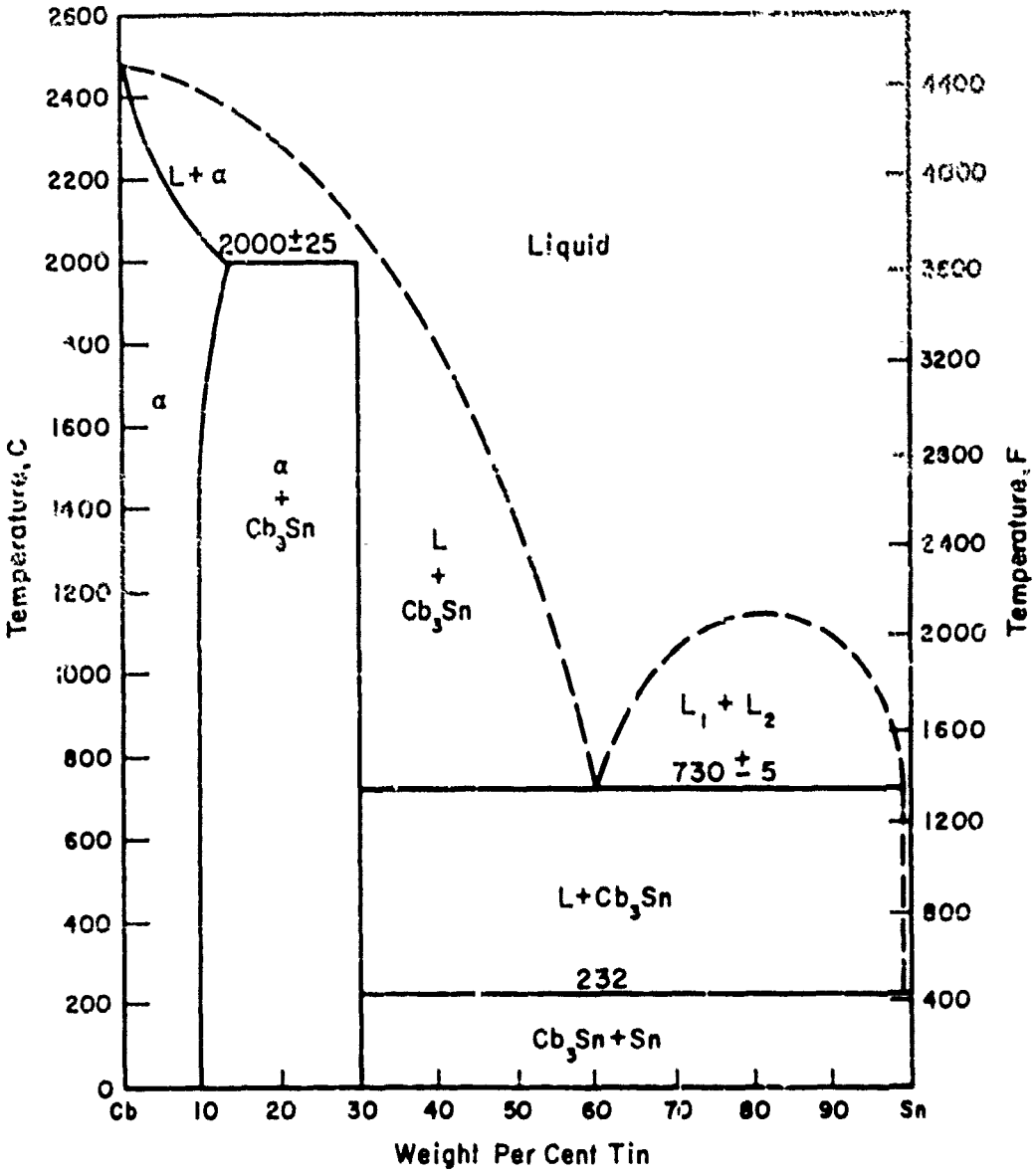
The columbium-tantalum system forms a continuous series of solid solutions.[40, 41] Williams and Pechin[41] determined the location of the solidus curve for the system. The melting points of the pure metals are slightly lower than the accepted values and may be attributed to the presence of oxygen.

COLUMBIUM-THORIUM SYSTEM

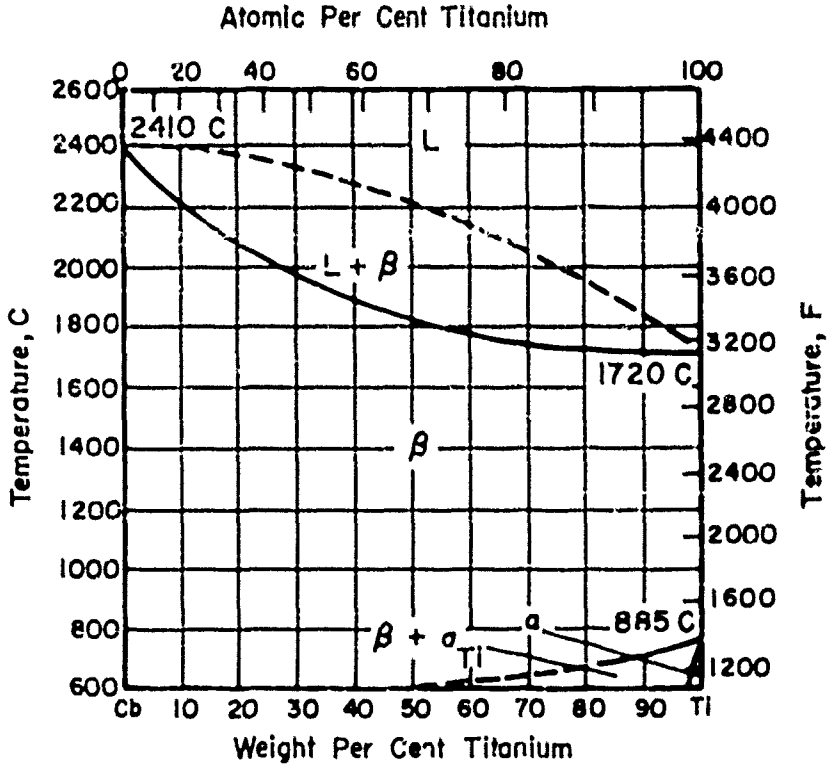


There are no compounds in the system. A eutectic reaction occurs at 1435 C and 8 weight per cent columbium. Solubility of columbium is very limited in all terminal phases. The maximum solubility is less than 1 weight per cent columbium at 1435 C, and less than 0.1 weight per cent in alpha thorium. Thorium solubility in columbium is negligible.[44]

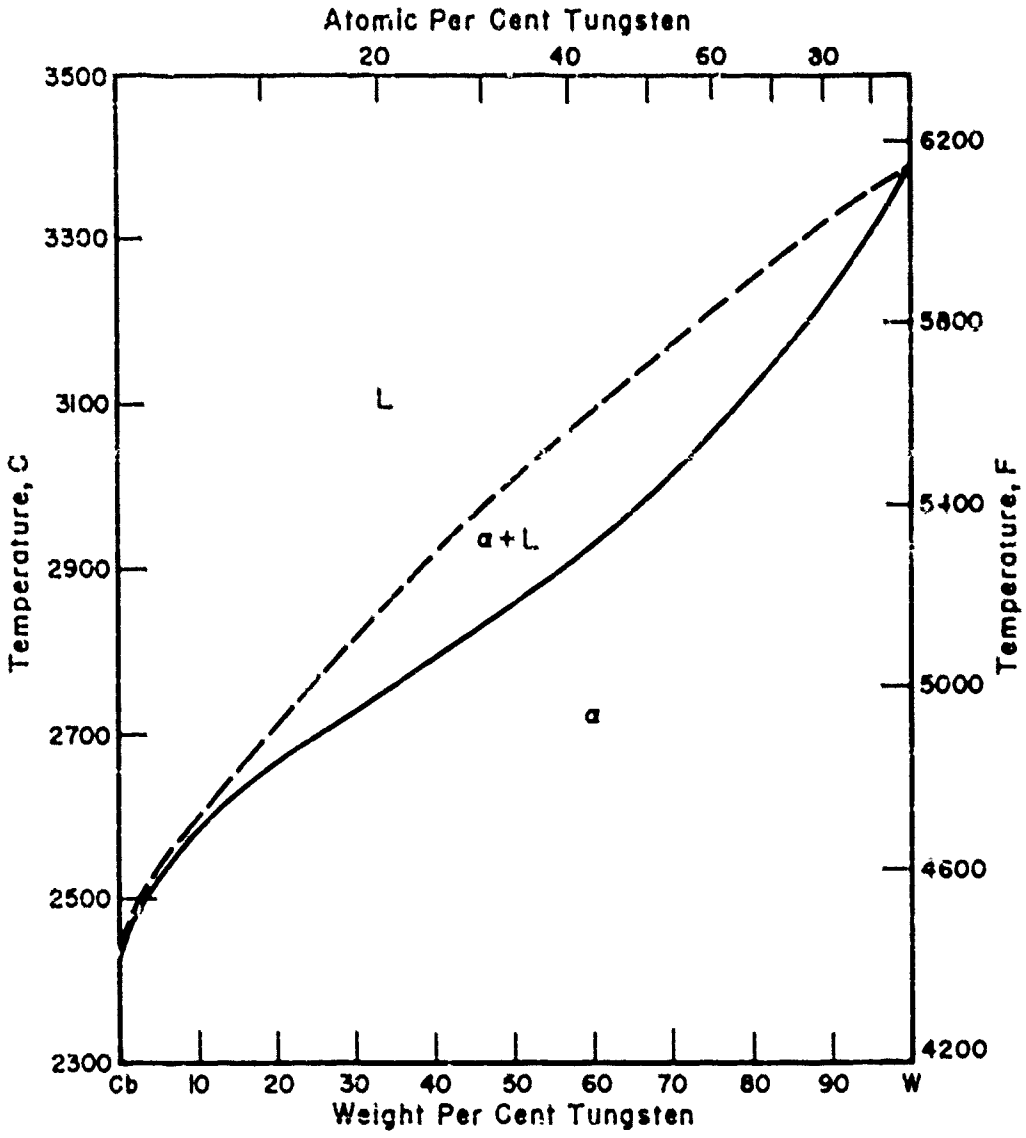
COLUMBIUM-TIN SYSTEM



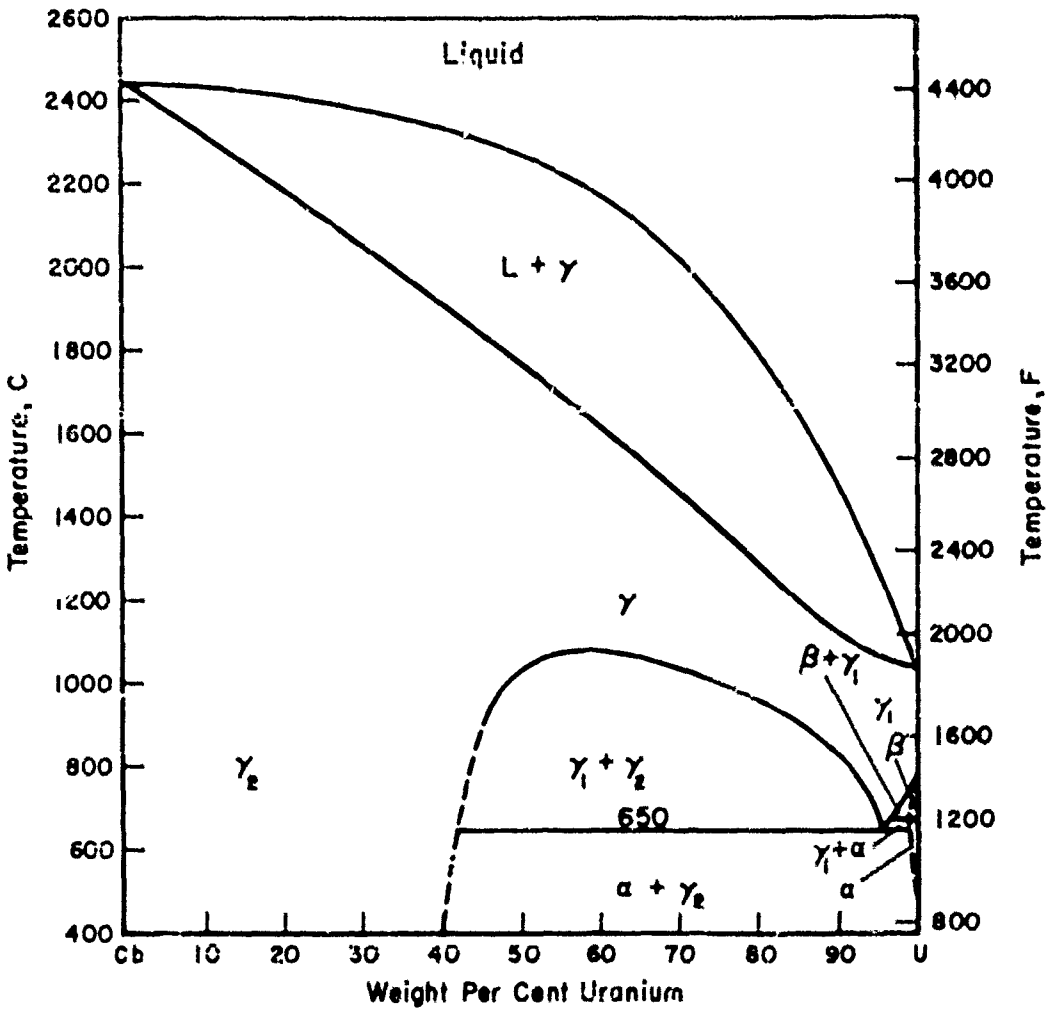
Cb_3Sn is a β-tungsten-type structure with a = 5.29 A.[35,39] The solid solubility of tin in columbium is 9.7 weight per cent at room temperature, increasing to 14 per cent at the peritectic temperature. The solubility of columbium in tin is less than 0.1 weight per cent at the melting point of tin.[38,39]



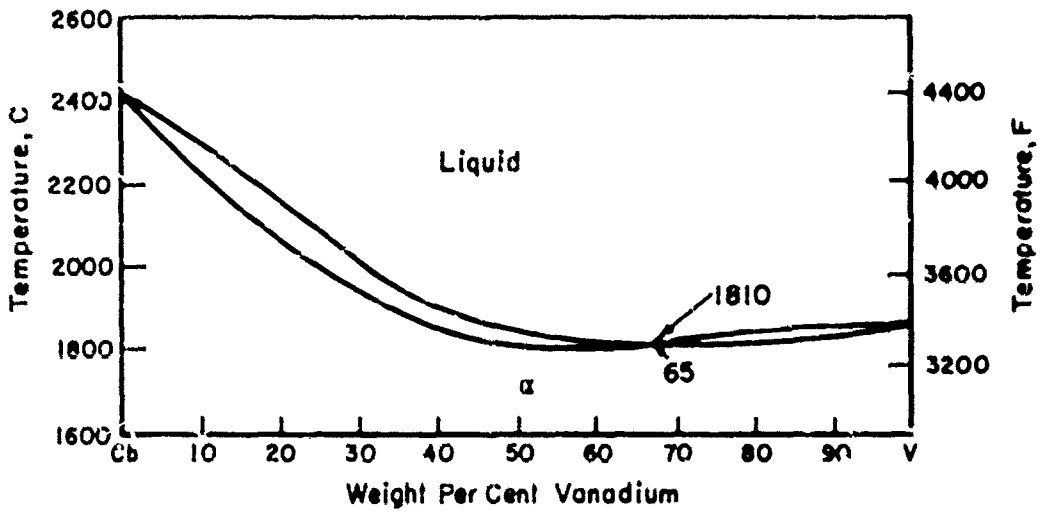
Beta-titanium and columbium form a continuous series of solid solutions.[43] Martensitic transformation occurs in alloys up to 28 weight per cent columbium under cooling rates of 100 to 10,000 deg/sec.[44] The minimum concentration for retaining bcc beta structure by quenching is 36 per cent columbium.[45]



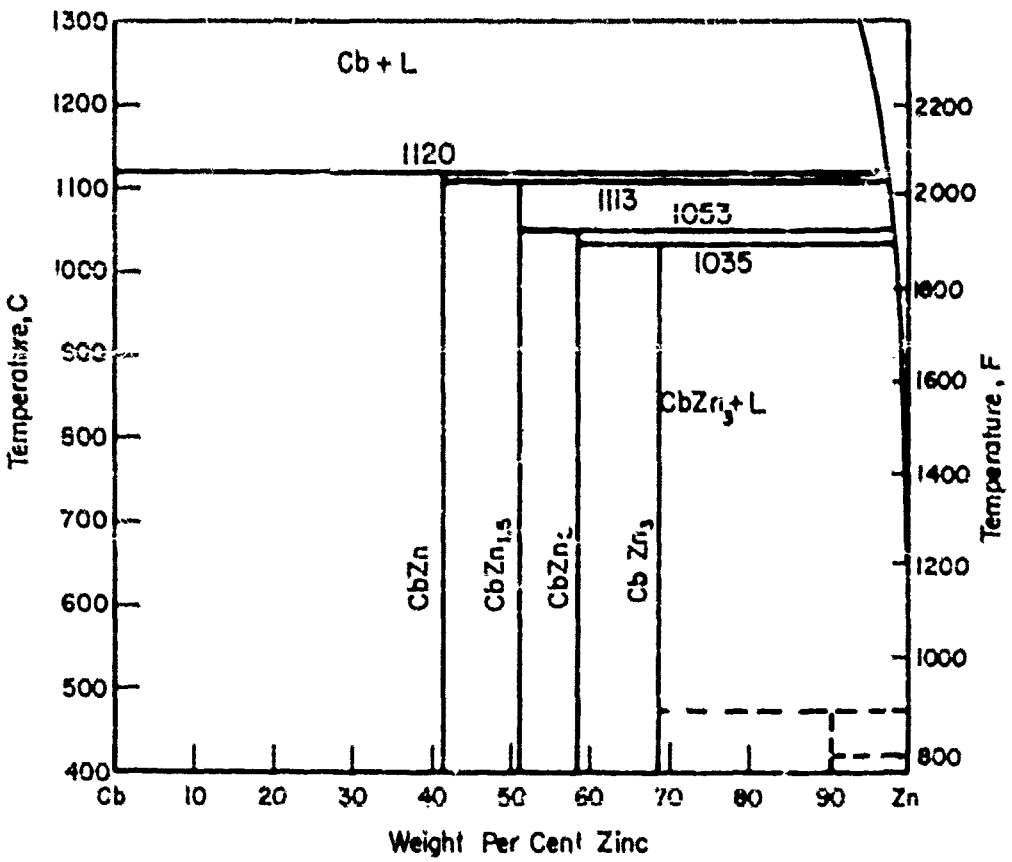
Mikheev and Pevzner[51] Von Bolton[52], and Buckle[40] stated that the columbium-tungsten system formed a continuous series of solid solutions.



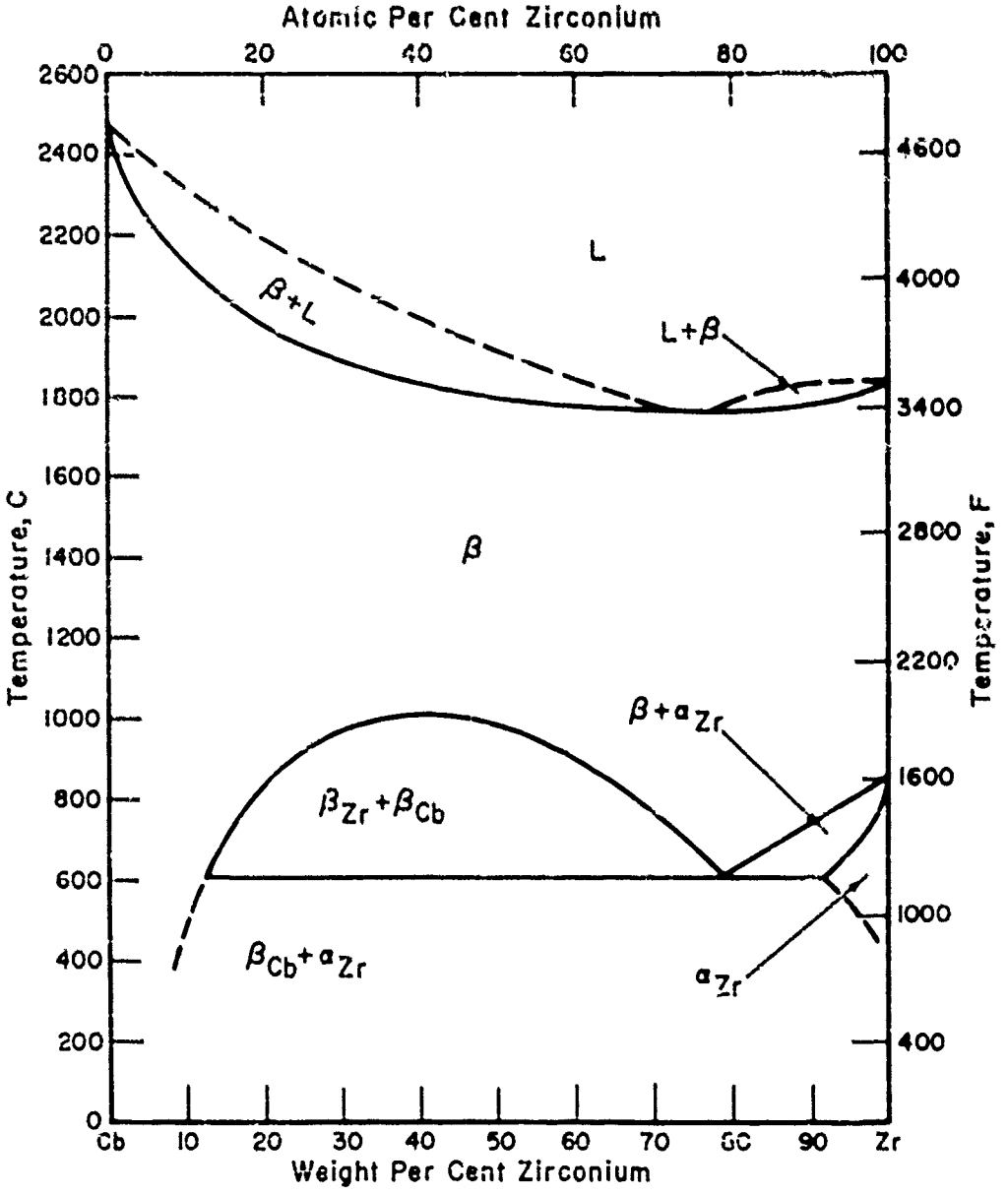
Columbium and gamma uranium form a continuous series of solid solutions above 950 C.[46-49] The monotectoid reaction occurs between 91 and 93 weight per cent uranium at 635 to 645 C.[46,47,49] The alpha-to-beta transformation occurs by a peritectoid reaction.[47-49]



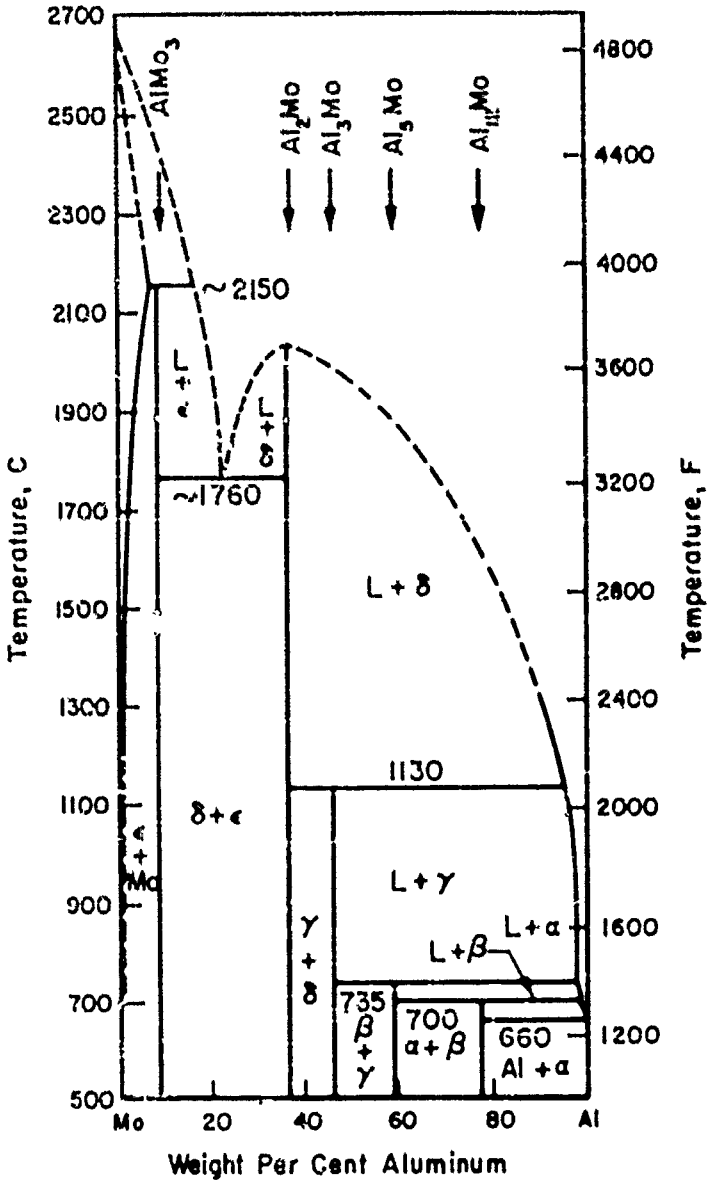
Wilhelm, Carlson, and Dicklnson found that the system was a continuous series of solid solutions.[50]



$CbZn_3$ is a cubic $AuCu_3$-type structure with a = 3.93 A.[229-231] $CbZn_{1.5}$ is hexagonal with a = 5.383 A and c = 26.43 A. The structures of the other two compounds, CbZn and $CbZn_2$, have not been determined. The temperatures given for the peritectic reactions represent equilibrium temperatures under 6 to 8 atmospheres pressure of zinc vapor.[229] Two unidentified phases possibly form by peritectic reaction at the low-temperature zinc-rich portion of the diagram. A eutectic is suspected at less than 0.2 weight per cent columbium, a few degrees below the melting point of zinc. No solubility of zinc in columbium has been found.[230]

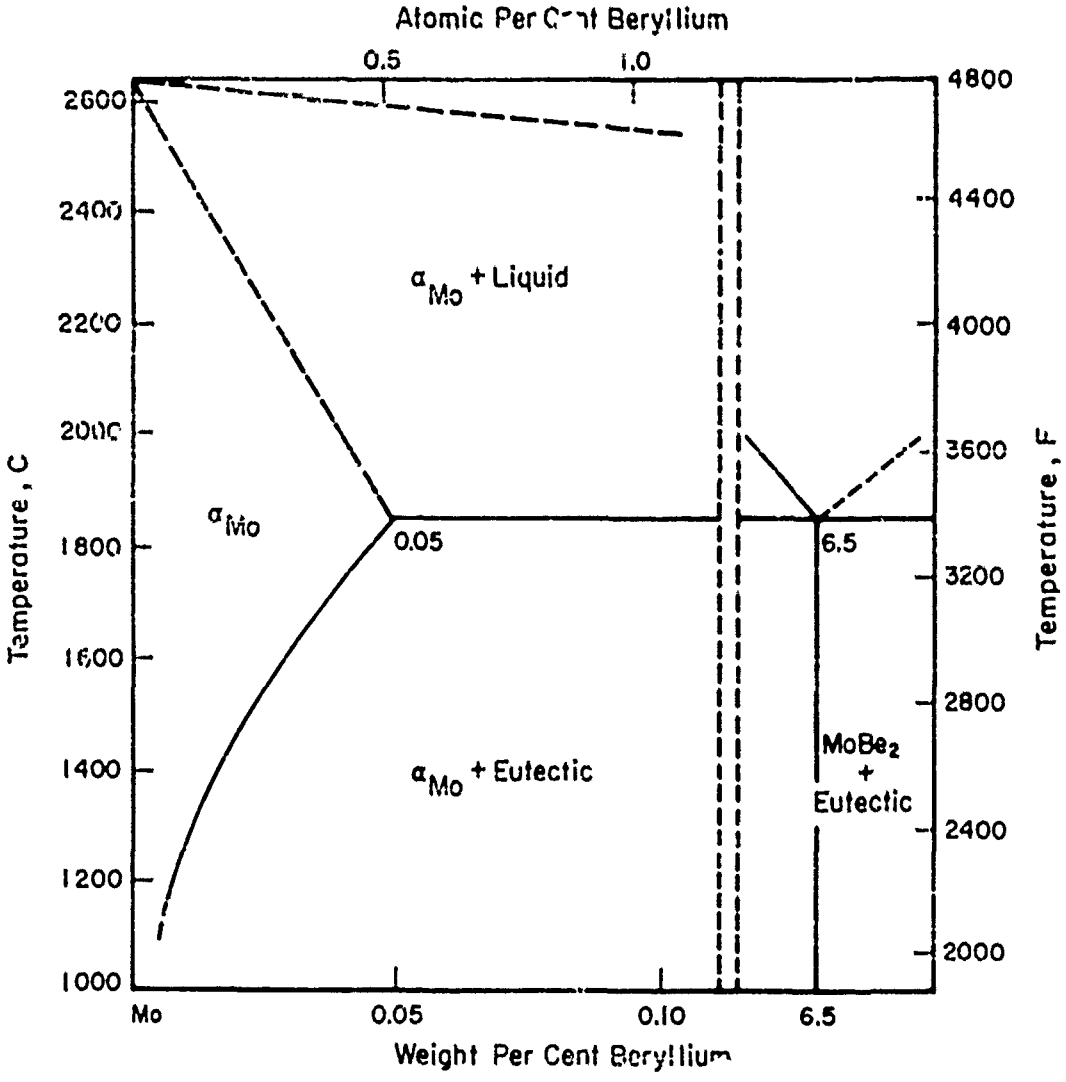


The diagram developed by Rogers and Atkins shows that complete solid solubility exists above 1000 C.[53] A eutectoid occurs at approximately 625 C and 32.5 weight per cent zirconium. The horizontal extends from 13 to 93.5 per cent zirconium. Domagala placed the eutectoid temperature at 800 C, with the continuous series of solid solutions existing above 1180 C.[54]

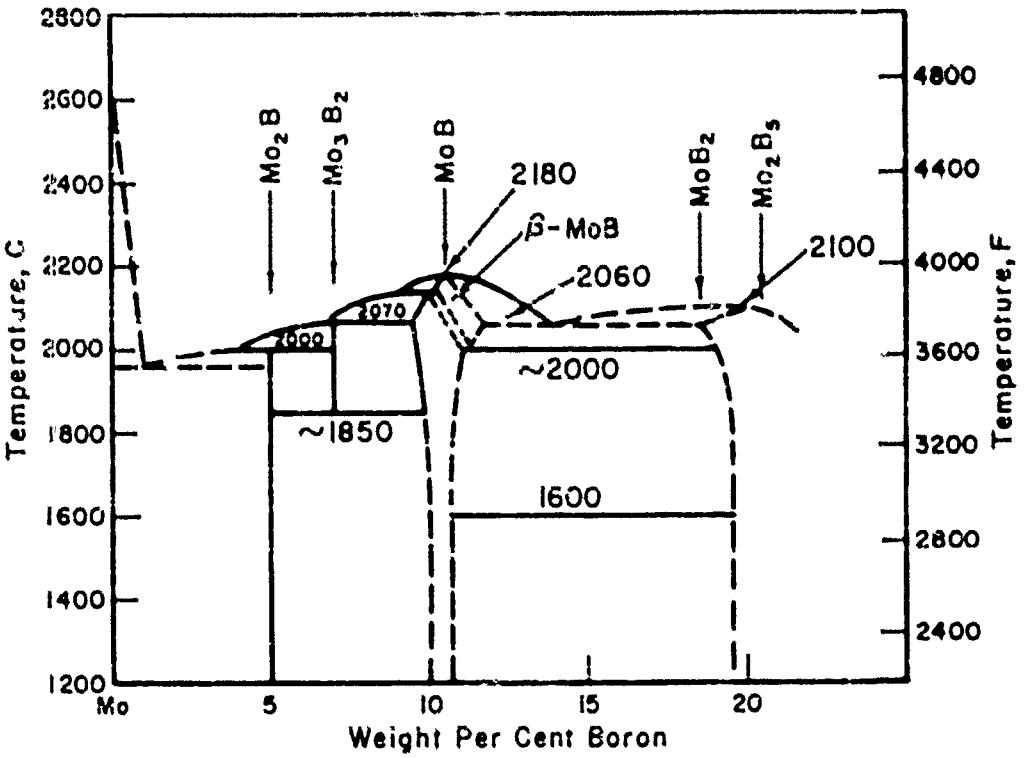


$AlMo_3(\epsilon)$ has the structure of β-W(A15) with a = 4.95 A.[55] The crystal structure of $Al_2Mo(\delta)$ has not been determined. $Al_3Mo(\gamma)$ is tetragonal with a = 6.297 A and c/a = 1.588.[56] $Al_5Mo(\beta)$ has a hexagonal structure isomorphous with Al_5W with a = 4.89 A and c/a = 1.80.[56] $Al_{12}Mo(\alpha)$ is body-centered cubic with a = 7.573 A, 26 atoms per unit cell, and is isotypic with WAl_{12}.[57] The solubility of aluminum in molybdenum is 6.4 weight per cent at 2150 C and 1.5 weight per cent at 1200 C.[58]

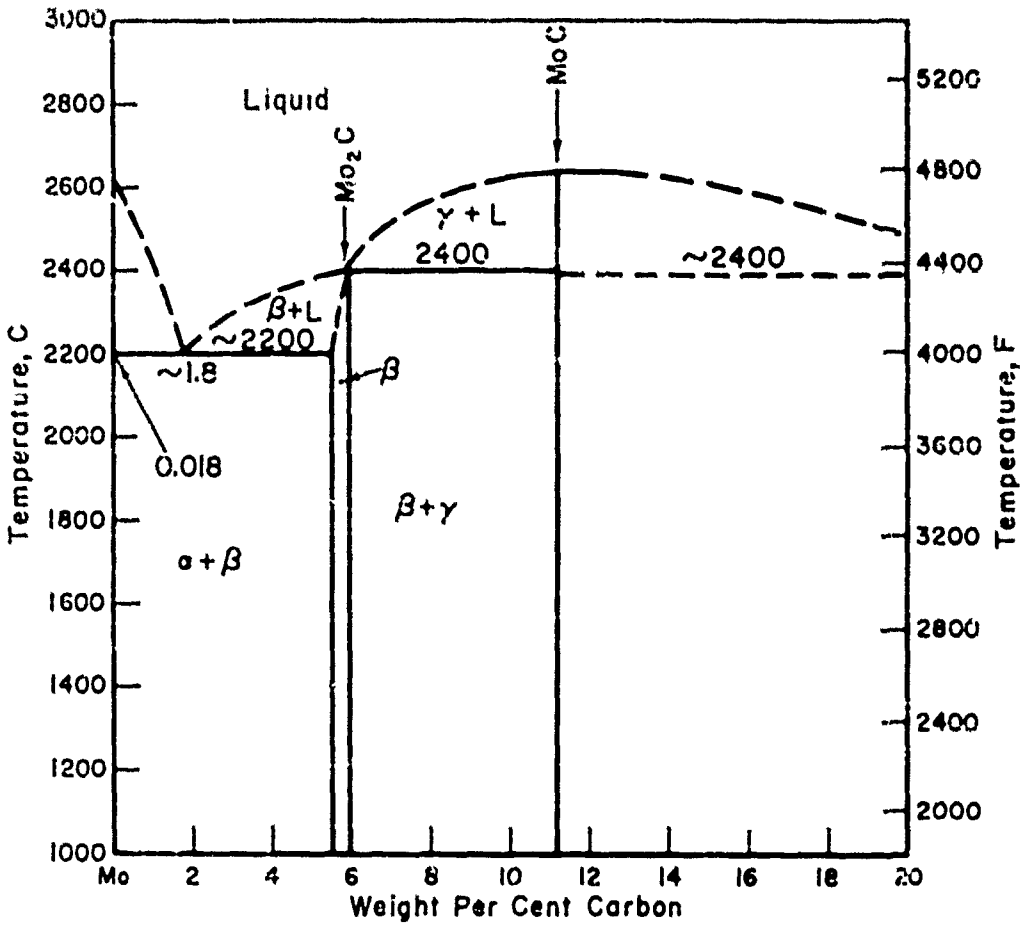
MOLYBDENUM-BERYLLIUM SYSTEM



Two intermediate phases occur in the system. Be_2Mo has a hexagonal $MgZn_2$(C14) type of structure with a = 4.433 A and c = 7.341 A.[61] $Be_{12}Mo$ is body-centered tetragonal with a = 7.27 A, c = 4.23 A, with 26 atoms per unit cell.[62] There is a eutectic at approximately 6.5 per cent beryllium and 1870 C.[63,64]

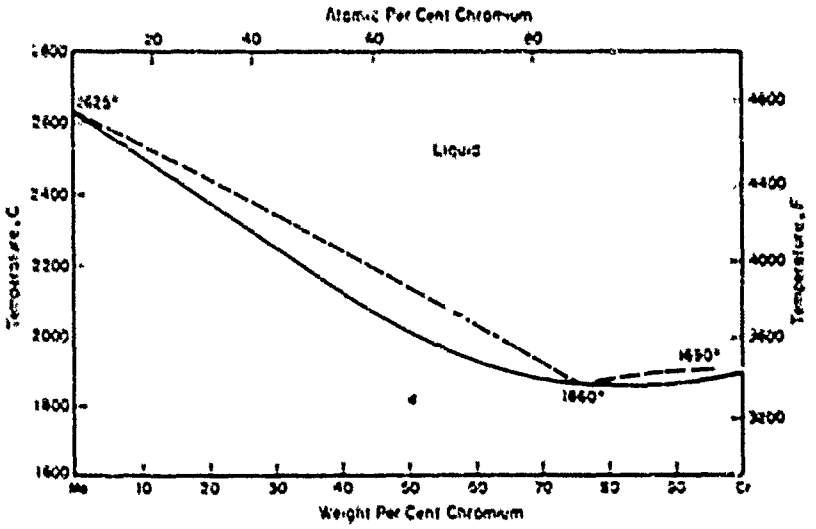


The following borides have been identified: Mo_2B is tetragonal of the $CuAl_2$(C16) type with a = 5.543 A, c = 4.735 A, and c/a = 0.854.(58,59) Mo_3B_2 is tetragonal and isotypic with Cr_3B_2. The low-temperature form of MoB is tetragonal with 8 MoB molecules per unit cell, and a = 3.110 A, c = 16.95 A, and c/a = 5.45(58,59) The high-temperature modification, β-MoB, is orthorhombic and isotypic with CoB, CbB, and TaB, with a = 3.16 A, b = 8.61 A, and c = 3.08 A.(59) MoB_2 is a hexagonal AlB_2 (C32) type, with a = 3.06 A, c = 3.10 A, and c/a = 1.01.(59) Mo_2B_5 is rhombohedral with the hexagonal axis a = 3.011 A, c = 20.93 A, and c/a = 6.95.(58,59) A Climax Molybdenum Report(60) gives the eutectic temperature as 2180 C and a composition of 2.75 per cent boron, a value which differs from the results obtained by Steinitz.(59)

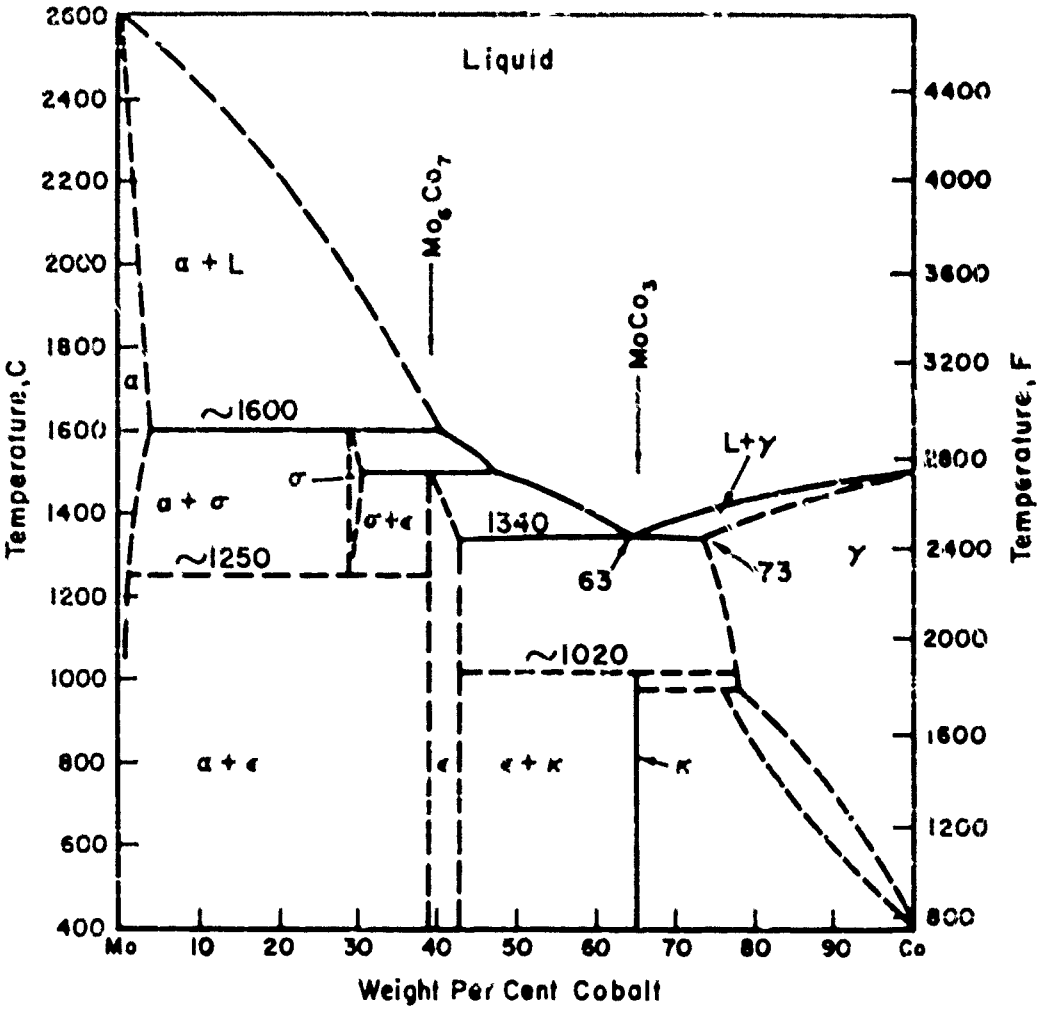


Carbon dissolves interstitially up to 0.013 weight per cent.[65] Mo_2C is a hexagonal W_2C-type structure with a = 3.002 Å, c = 4.724 Å, and c/a = 1.574.[66,67] The hexagonal phase MoC is isotypic with WC. There is disagreement on the values for the lattice parameters. Kuo gives the values as a = 2.898 Å, c = 2.809 Å, and c/a = 0.969, with one molybdenum atom per unit cell.[67] Nowotny reported the lattice constants a = 3.01 Å, c = 14.61 Å, and c/a = 4.86, with 12 atoms of molybdenum per unit cell.[68]

MOLYBDENUM-CHROMIUM SYSTEM

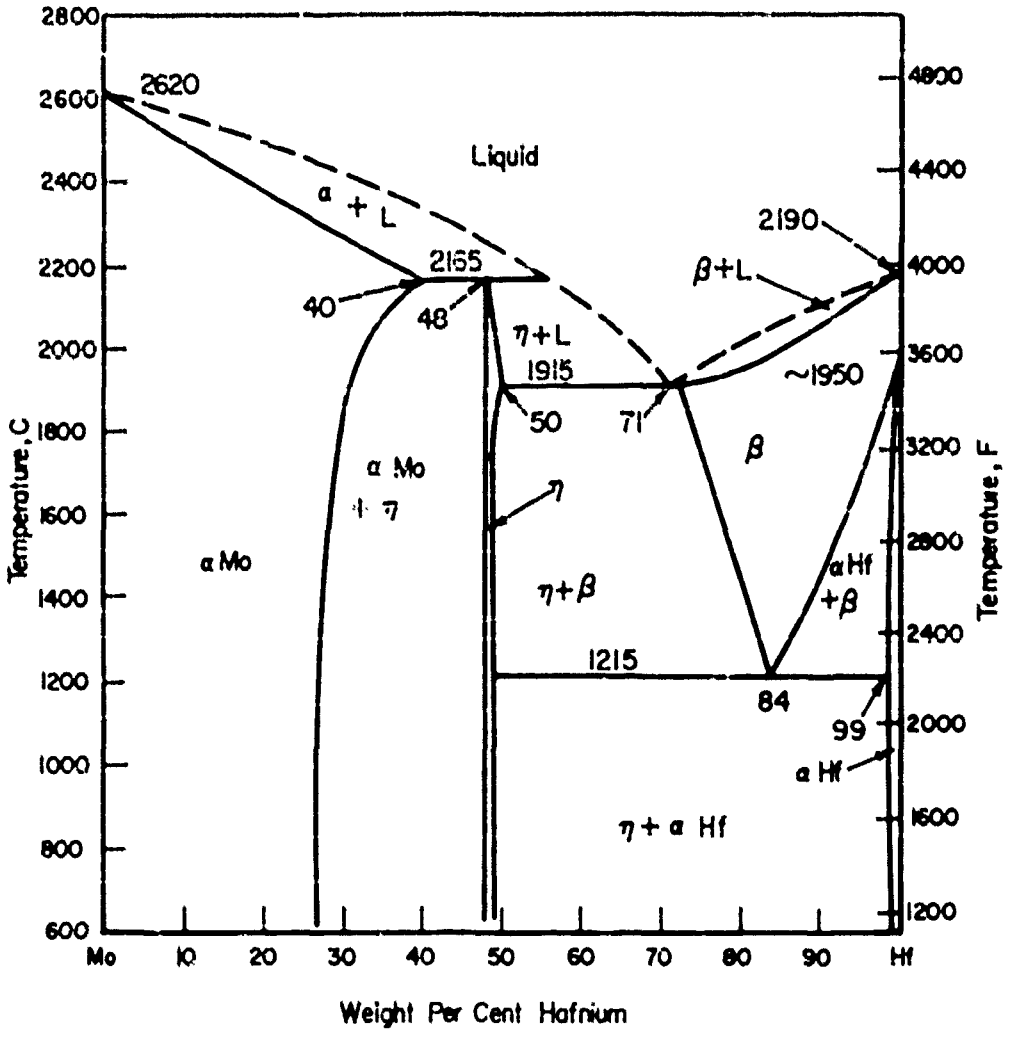


The molybdenum-chromium system forms a continuous series of solid solutions at high temperatures.[15, 64, 71] A minimum in the melting point occurs at approximately 80 weight per cent chromium and 1860 C.[71] Evidence of a phase transformation in alloys up to 40 weight per cent chromium has been found.[71]

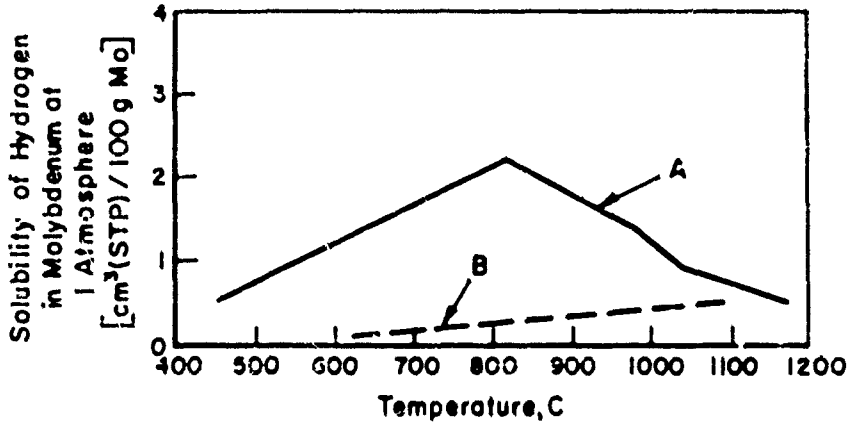


The solid solubility of cobalt in molybdenum was found to be 2.75, 1.75, 1.4, 0.9o, and 0.6 weight per cent at 1480, 1375, 1300, 1200, and 1100 C.[69] Mo_6Co_7 is rhombohedral-hexagonal and isotypic with W_6Fe_7 ($D8_5$ type). Its lattice parameters are a = 8.890 A, α = 30°48' at the ideal composition, and a = 8.873 A, α = 30°53' if saturated with cobalt.[70] The structure of $MoCo_3$ is similar to that of WCo_3. This phase is isotypic with Ni_3Sn ($D0_{19}$ type).[70]

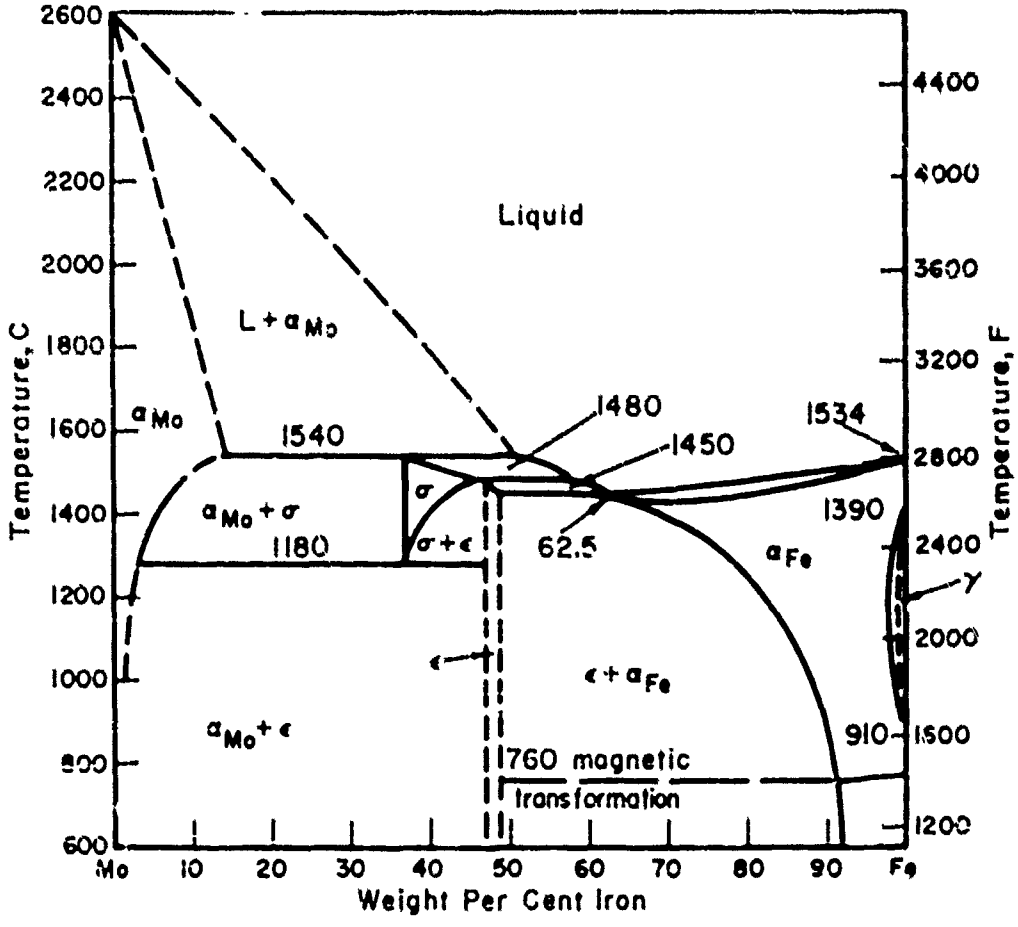
MOLYBDENUM-HAFNIUM SYSTEM



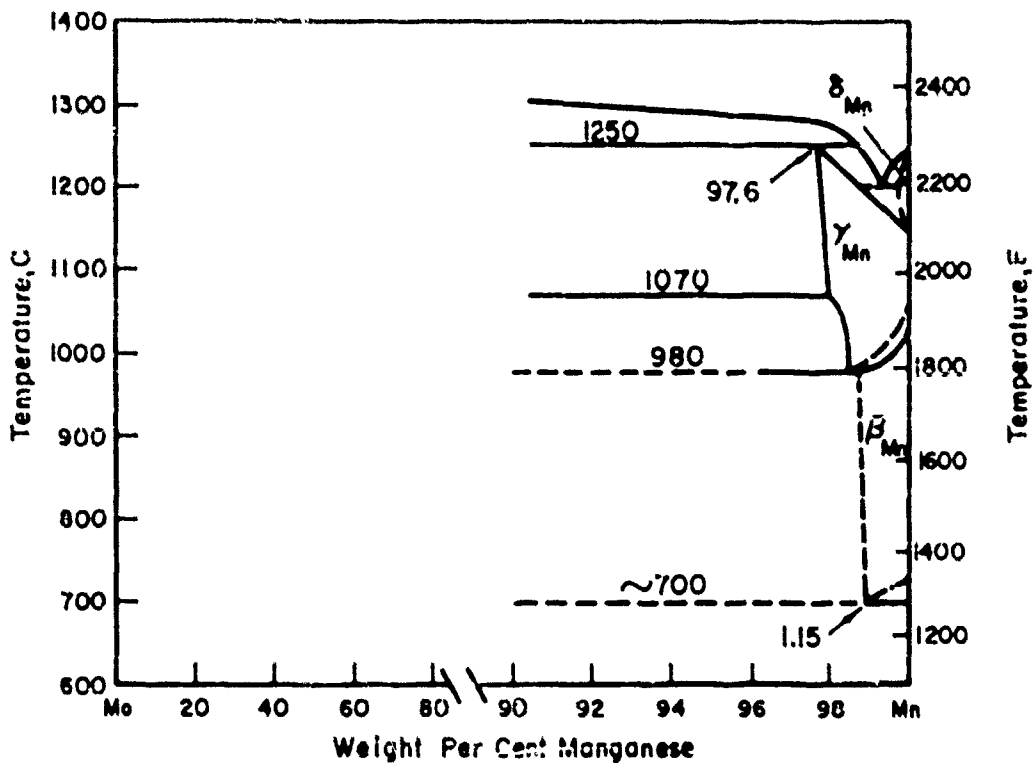
The intermediate Laves η-phase, Mo_2Hf, forms at 2180 C by a peritectic reaction. The crystal structure of this phase is a cubic Cu_2Mg (C15) type, with 8 molecules per unit cell. Its lattice parameter is 7.560 A. The solubility of hafnium in molybdenum is 40 weight per cent (28 atomic per cent) at 2180 C, decreasing to 28 weight per cent (16.5 atomic per cent) at 900 C.(78)



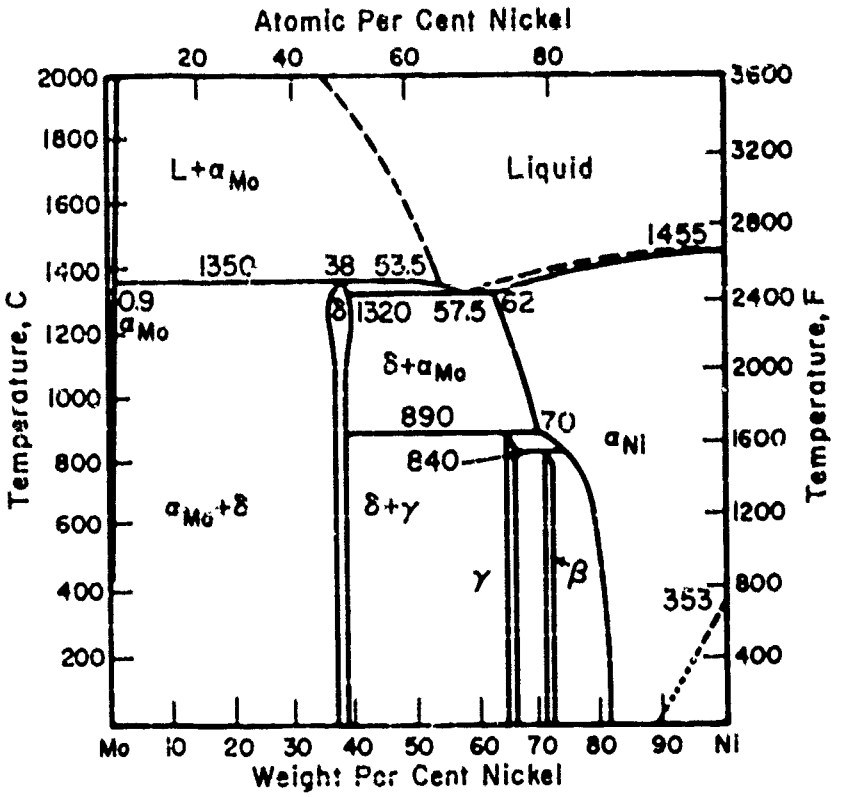
Shown are the results of two determinations of the solubility of hydrogen in solid molybdenum. Curve A was determined by Martin[76], Curve B by Sieverts and Brüning.[77]



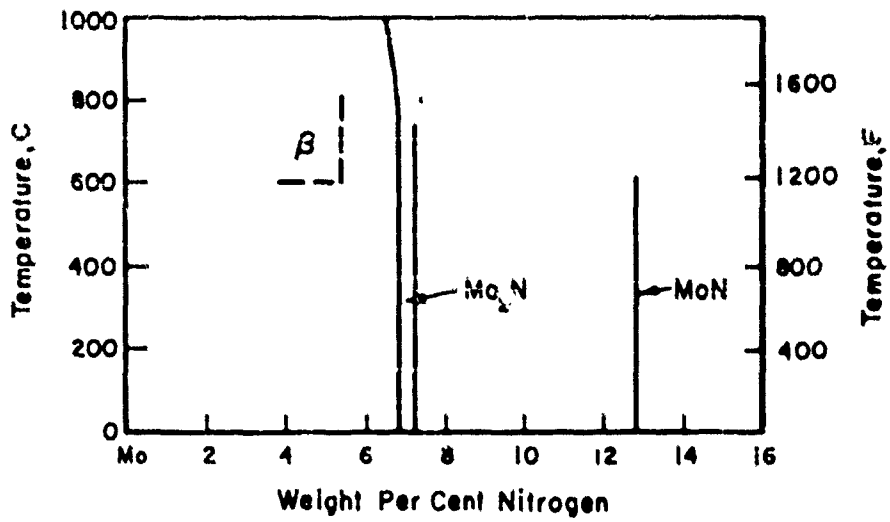
The ε-phase is rhombohedral of the W_6Fe_7 (D8$_5$) type, with a = 8.99 A, α = 30°38.8'.(72, 73) The structure of the σ-phase is tetragonal, with a = 9.185 A, c = 4.812 A, and c/a = 0.5237 at 36 weight per cent iron (50 atomic per cent). There are 30 atoms per unit cell.(74) The solubility of iron in molybdenum is 10.5, 8.7, 4.8, 3.6, and 2.7 weight per cent at 1480, 1400, 1300, 1200, and 1100 C, respectively.(75)



A sigma phase of 50.1 weight per cent (63.7 atomic per cent) is stable above 1115 C. It has a tetragonal structure with a = 9.10 A, c = 4.74 A, and c/a = 0.52, and ordered atomic arrangement.[79, 80] Twenty weight per cent manganese was found dissolved in alloys fast-cooled (600 C per minute) from 1800 C. Only about 10 per cent remained in solution after slow cooling to room temperature.[81] Another intermediate phase, possibly stable only above 1100 C, exists between 80 and 88 atomic per cent manganese.[82]



MoNi (δ) forms by a peritectic reaction at approximately 1350 C.[85] $MoNi_3$ (γ) is hexagonal close packed with a = 2.54 A, and c/a = 1.65.[86] $MoNi_4$ (β) was reported to be a face-centered tetragonal superstructure with a = 3.62 A, c = 3.57 A, and c/a = 0.986.[85] Ham reported β to have an ordered face-centered tetragonal structure with a = 5.731 A, c = 3.571 A, and c/a = 0.623.[87] The solubility of nickel in molybdenum[88] is 0.8, 0.75, 0.65, and 0.5 weight per cent at 1340, 1315, 1290, and 1200 C, respectively.



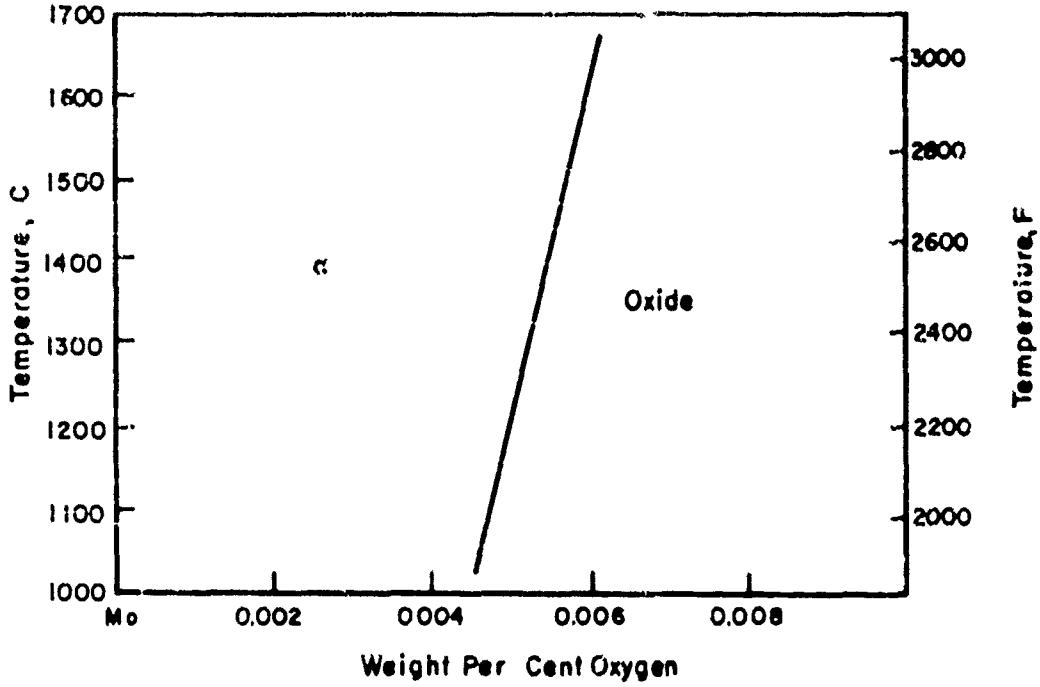
The β-phase, stable only above 600 C, has a face-centered tetragonal lattice of the molybdenum atoms with a = 4.18 A, c = 4.02 A, and c/a = 0.961, after quenching from above 850 C. The position of nitrogen atoms is unknown.(83) Mo_2N is face-centered cubic with a = 4.163 A on the molybdenum side to a = 4.168 A on the nitrogen side. MoN has a hexagonal superstructure consisting of 16 atoms per unit cell with a = 5.725 A, c = 5.608 A, and c/a = 0.980.(84)

MOLYBDENUM-OSMIUM SYSTEM

The molybdenum-osmium system is in its final stages of development by Taylor.[170] He found the solubility of osmium in molybdenum to range from about 10 weight per cent at 1000 C to 30 weight per cent at 2350 C. A β-tungsten-type phase, Mo_3Os, forms around 2200 C. It is stable over a limited composition range at about 40 weight per cent osmium. A sigma phase, Mo_3Os_2, forms by a peritectic reaction at approximately 2400 C and 45 weight per cent osmium. It is stable over a composition range of about 10 weight per cent at 1000 C. Molybdenum is soluble in osmium up to 25 weight per cent at 1000 C, increasing to about 30 weight per cent at 2400 C.

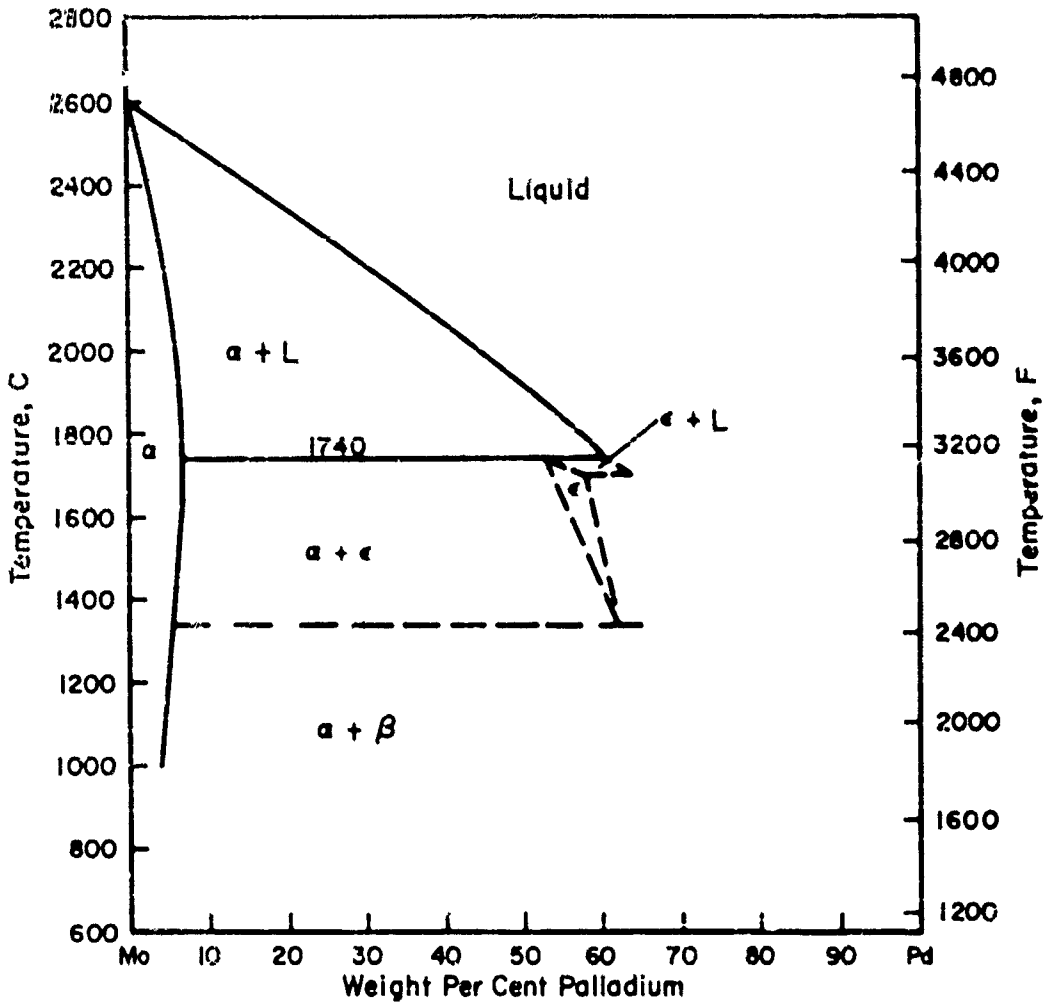
No diagram is available at this time.

4/61



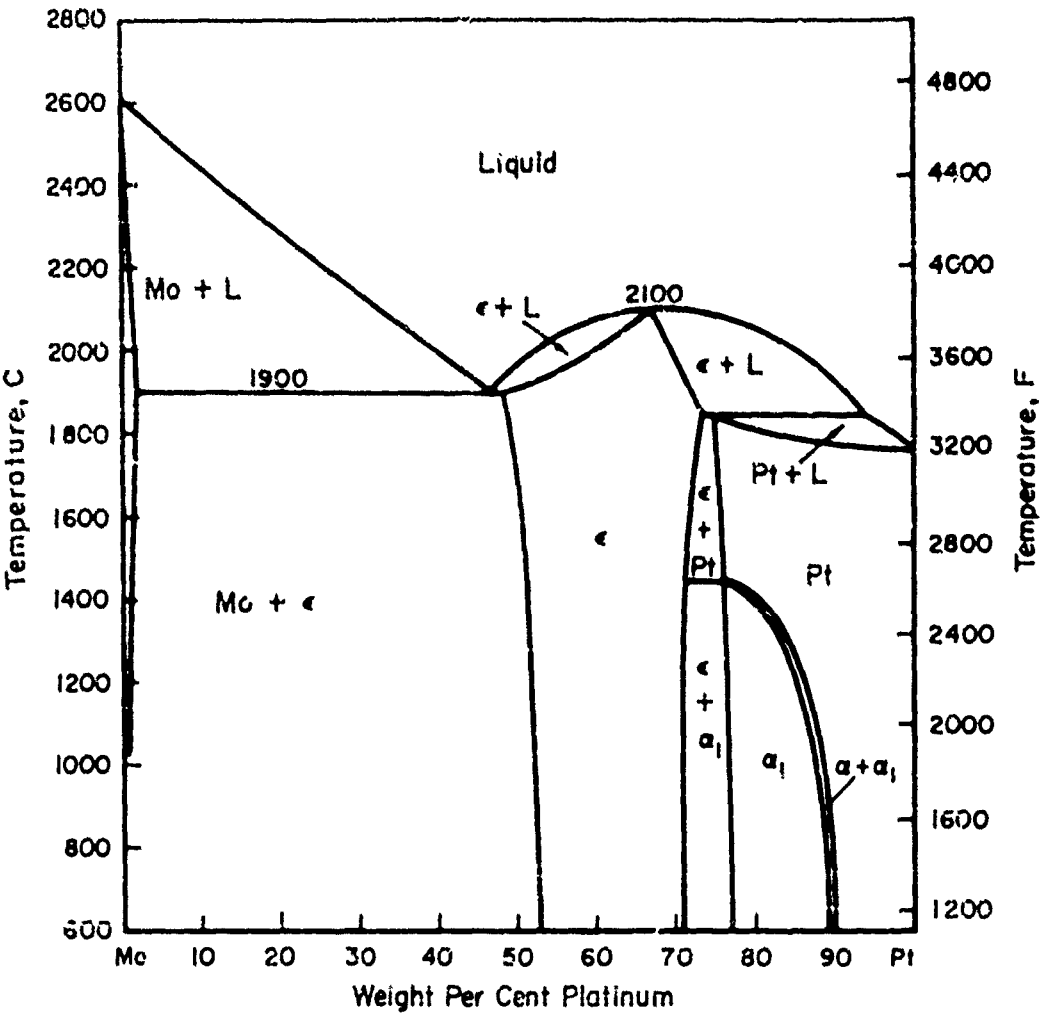
The solubility of oxygen in molybdenum was determined by Few and Manning.[89] The line represents a three-phase equilibrium between gaseous oxygen, molybdenum oxide, and oxygen dissolved in metallic molybdenum. The composition of the oxide was not determined.

MOLYBDENUM-PALLADIUM SYSTEM



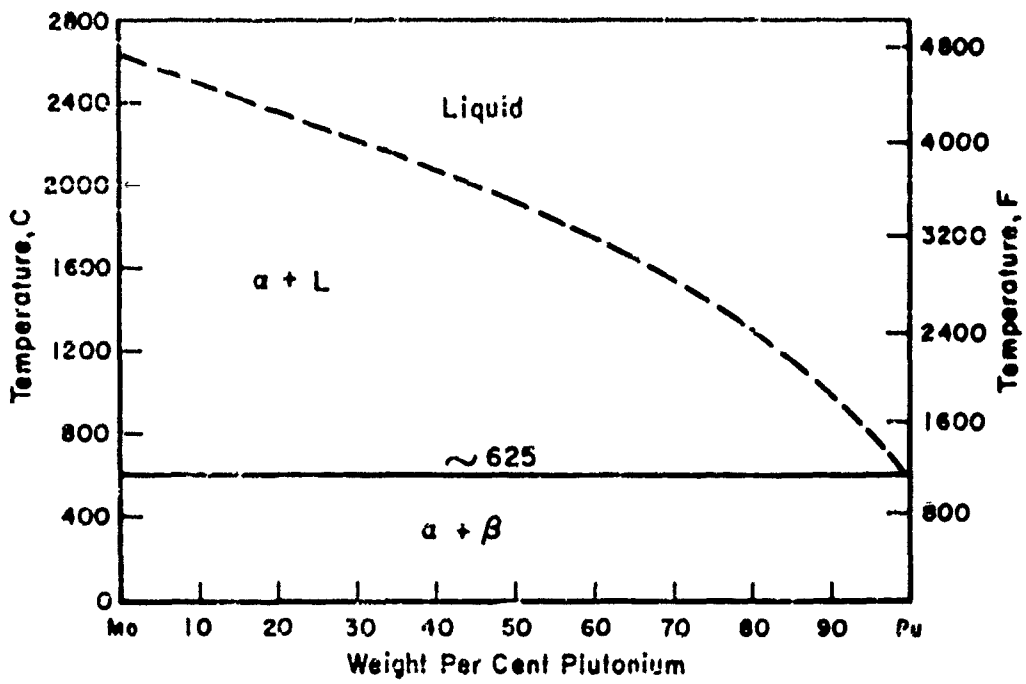
The intermediate phase ε is hexagonal close packed, formed by a peritectic reaction at 1740 C. Haworth and Hume-Rothery established the existence of a slight solubility of palladium in molybdenum at high temperatures, 4 to 9 weight per cent palladium.(90) Their findings disagree with the solubility values obtained by Greenfield and Beck of up to 28 weight per cent palladium.(91) Raub determined that the solubility of molybdenum in palladium is 44.9 weight per cent molybdenum at 1200 C, decreasing to 33.2 per cent at 800 C.

MOLYBDENUM-PLATINUM SYSTEM

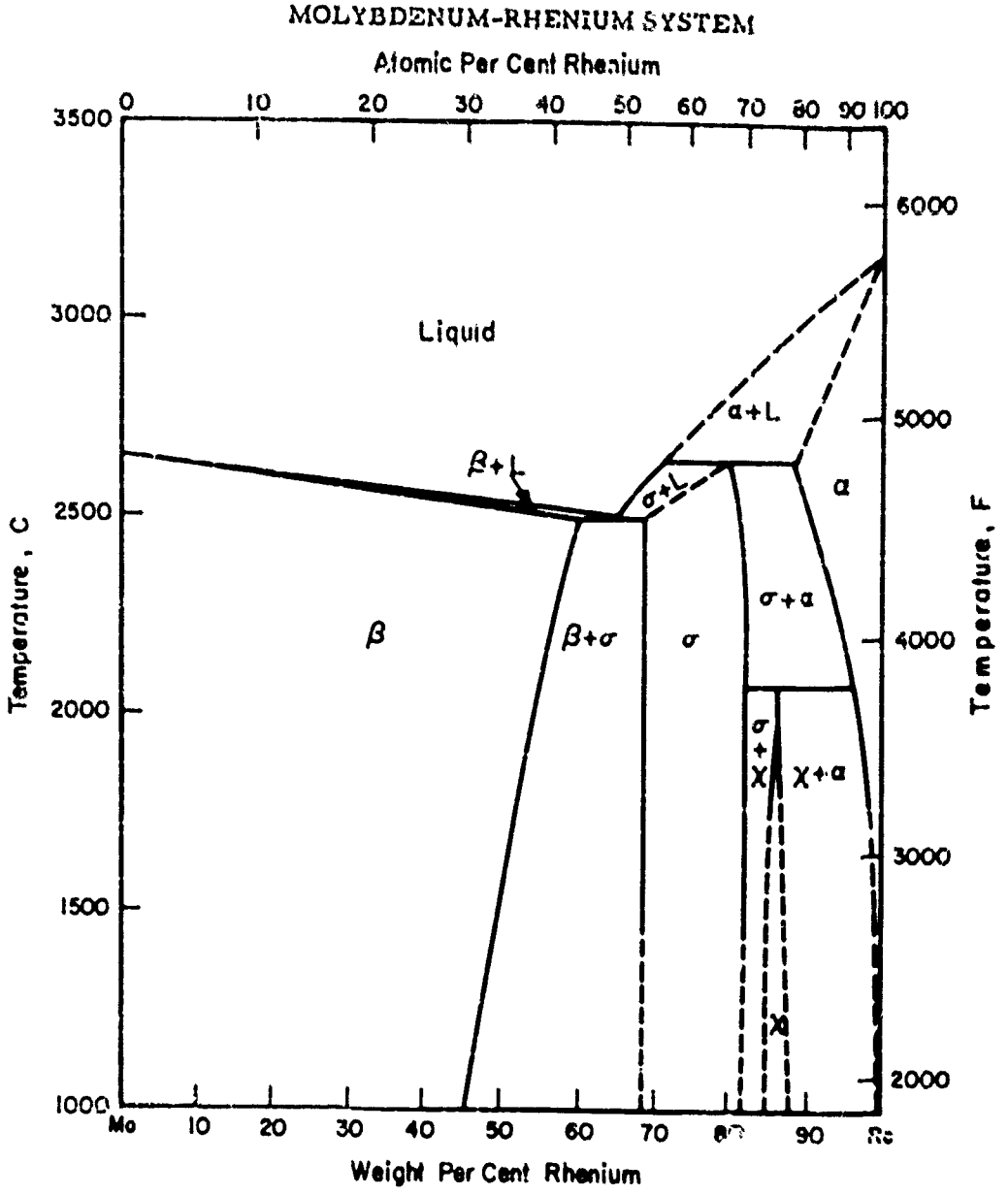


Knapton[32] verified Raub's findings[92] of an intermediate phase ε with a hexagonal-close-packed structure, with a = 2.80 A and c/a = 1.603, at the molybdenum side, and a = 2.786 A and c/a = 1.611, at the platinum side. α_1 is face-centered tetragonal with a = 3.896 A and c/a = 1.005 to 1.009. The solubility of platinum in molybdenum is very slight.

MOLYBDENUM-PLUTONIUM SYSTEM

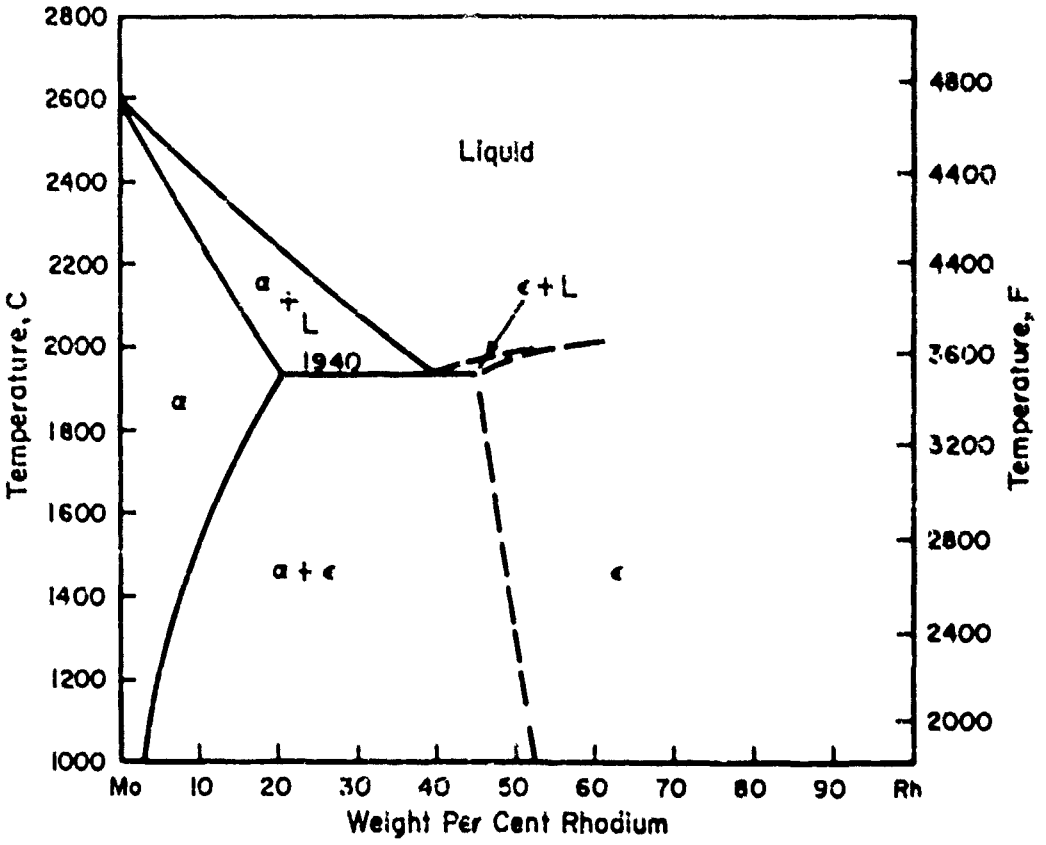


No intermediate phases have been found in this system.[29]

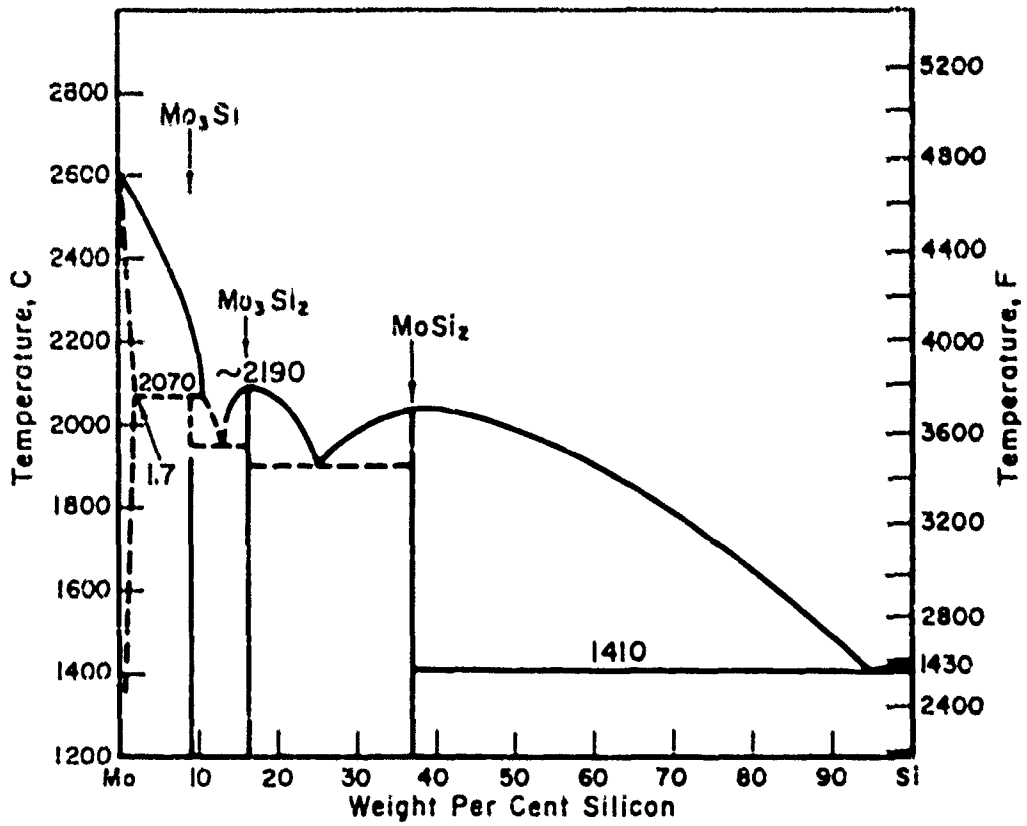


The σ-phase, Mo_2Re_3, is a tetragonal (D_{2h}^{14}) structure isomorphous with the σ-phase found in iron-chromium alloys.[94-97] The lattice parameters at 60 atomic per cent (73 weight per cent) are a = 9.588 A, c = 4.983 A, and c/a = 0.5197.[97] Knapton found the σ-phase to be stable only at 1150 C and above.[96] The body-centered cubic phase, χ, is isomorphous with α-manganese. It corresponds to an approximate composition of $MoRe_3$ with a = 9.55 A.[91,94] The solubility of rhenium in molybdenum ranges from 46 weight per cent at 1200 C to 59 weight per cent at the eutectic temperature, 2505 C.[94]

MOLYBDENUM-RHODIUM SYSTEM

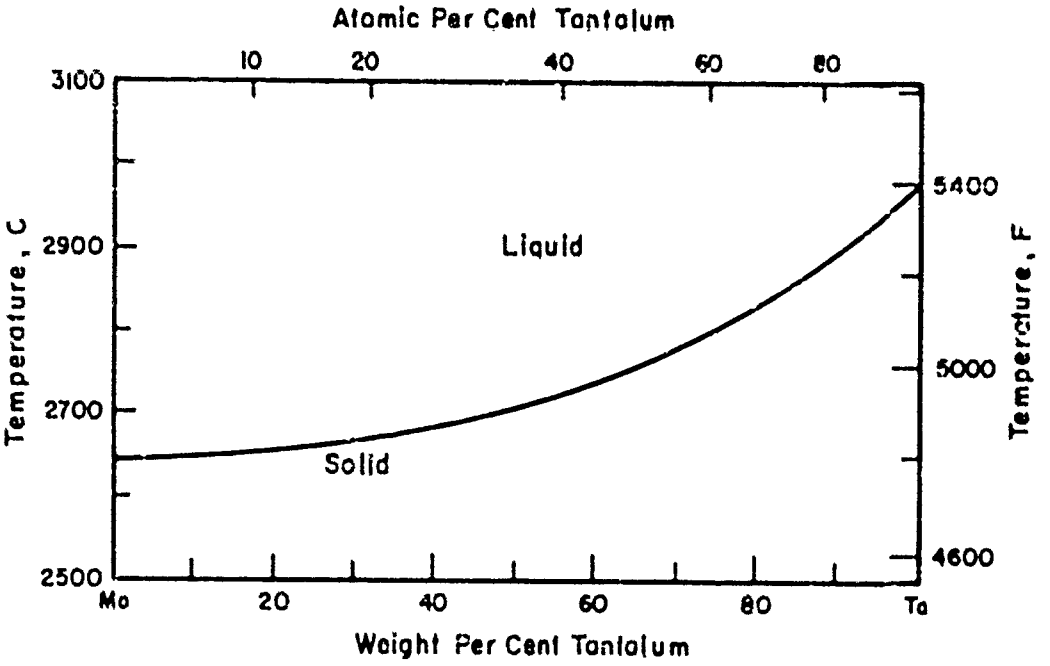


The system contains a eutectic at approximately 41 weight per cent (40 atomic per cent) rhodium. The maximum solubility of rhodium in molybdenum is approximately 21 weight per cent at the eutectic horizontal, diminishing to less than 3 weight per cent at 1100 C.[90] The ϵ-phase, is hexagonal close packed with a = 2.740 kX, c = 4.380 kX, and c/a = 1.599 at 60 weight per cent rhodium.[90, 92]



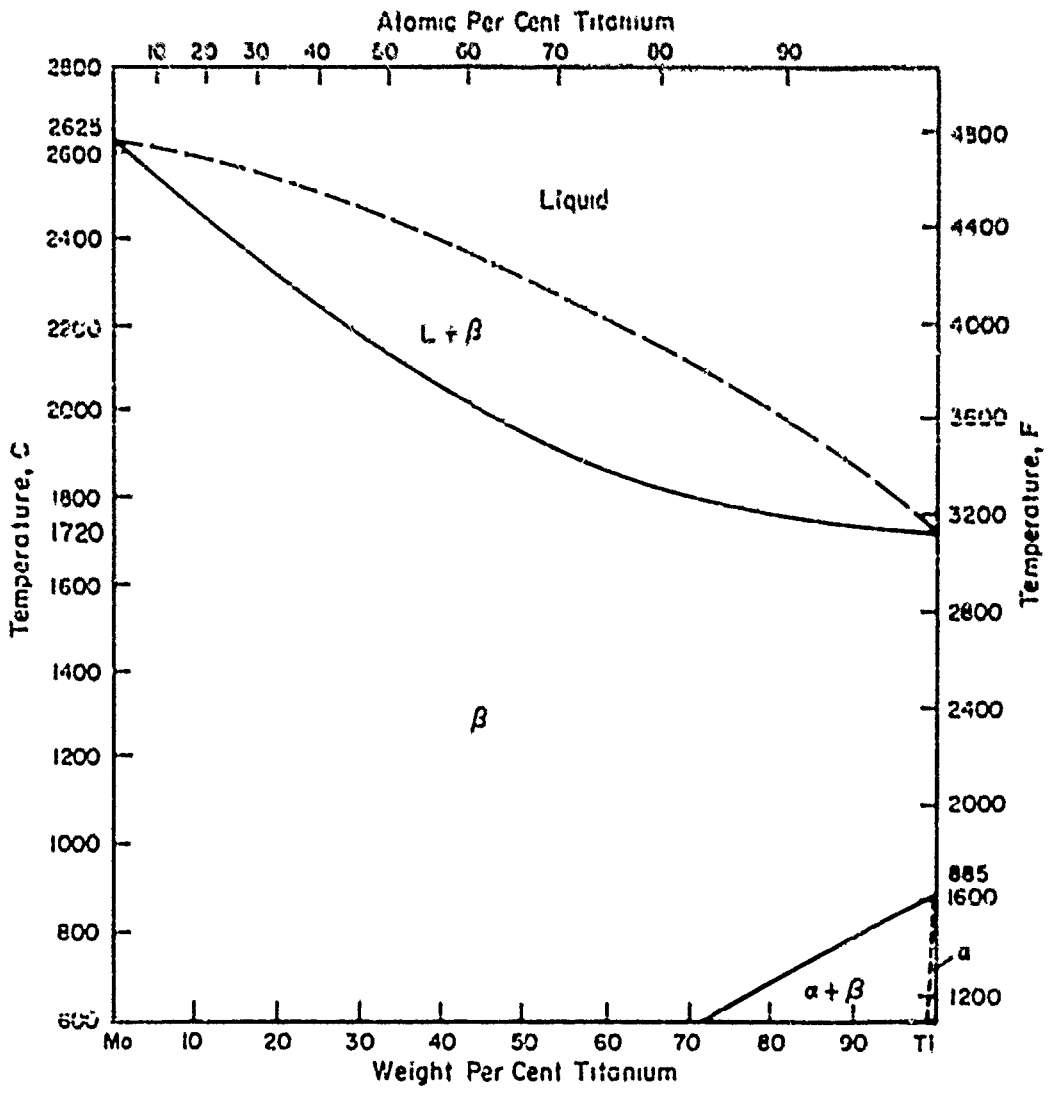
Mo_3Si is isotypic with β-tungsten (A15 type), a = 4.89 to 4.90 A.[98] Mo_3Si_2 is tetragonal with the dimensions a = 9.66 A, c = 4.90 A, and c/a = 0.51. The cell contains 6 Mo_3Si_2.[99] $MoSi_2$ is tetragonal, with 6 atoms per unit cell (C11b type), with a = 3.20 A, c = 7.88 A, and c/a = 2.462.[98]

MOLYBDENUM-TANTALUM SYSTEM

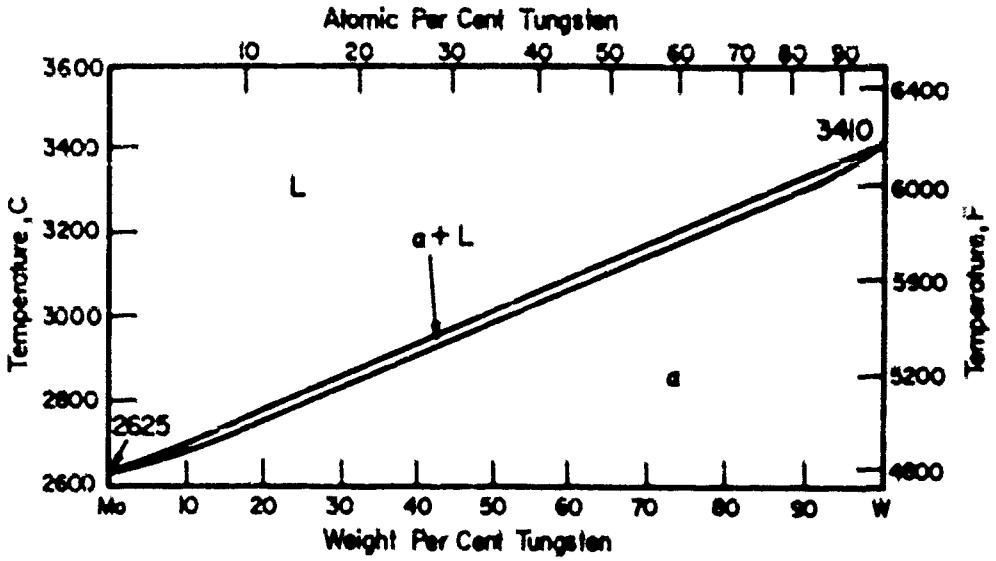


Molybdenum-tantalum alloys exhibit a continuous series of solid solutions.[40, 100, 101] Shown are the results of a melting-point study made by Geach and Summers-Smith.[101]

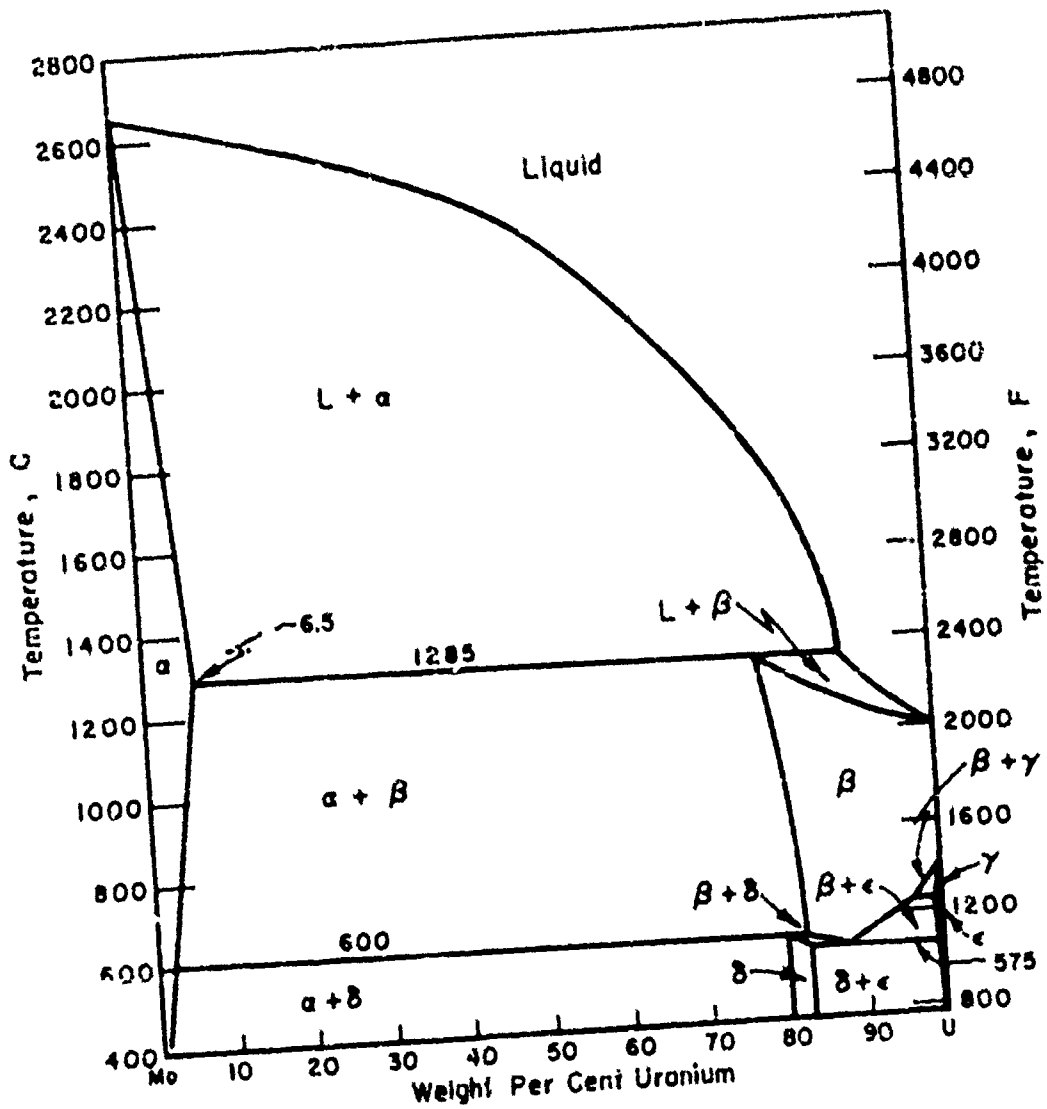
MOLYBDENUM-TITANIUM SYSTEM



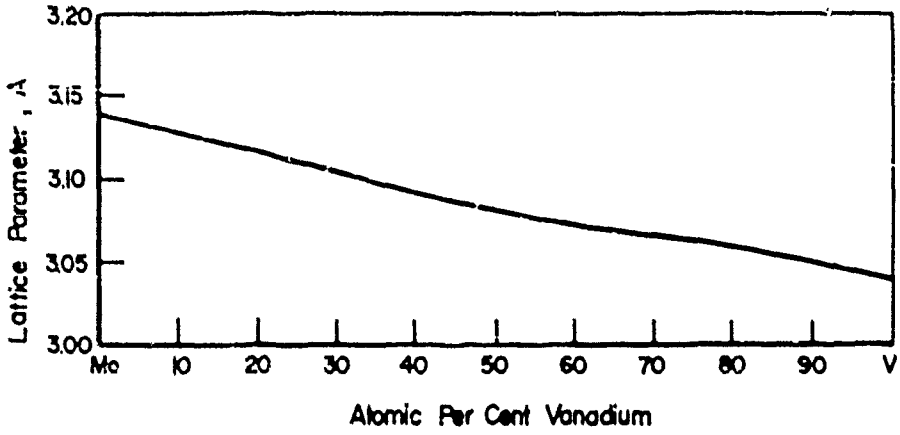
Molybdenum-titanium alloys exhibit a continuous series of solid solutions above 900 C.[102,103] The body-centered titanium-rich solution transforms to a hexagonal-close-packed structure below 885 C.[103,104]



Molybdenum and tungsten form a continuous series of solid solutions.[108,109,110]

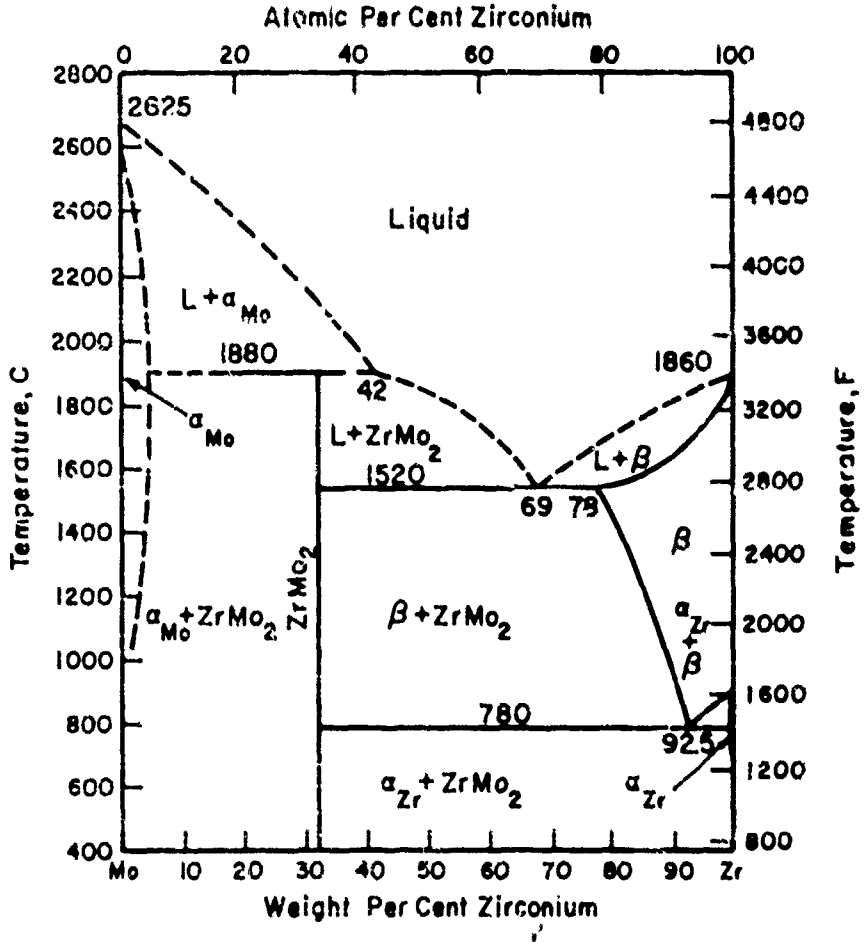


The crystal structure of the $\delta(MoU_2)$ phase is of the tetragonal $MoSi_2$ (C11b) type, with a = 3.427 A, c = 9.834 A, and c/a = 2.871.(106) The uranium-rich portion of the phase diagram was established by Saller(106) and Halteman.(105) The solubility of uranium in molybdenum is approximately 6.5 weight per cent at 1285 C.(106)



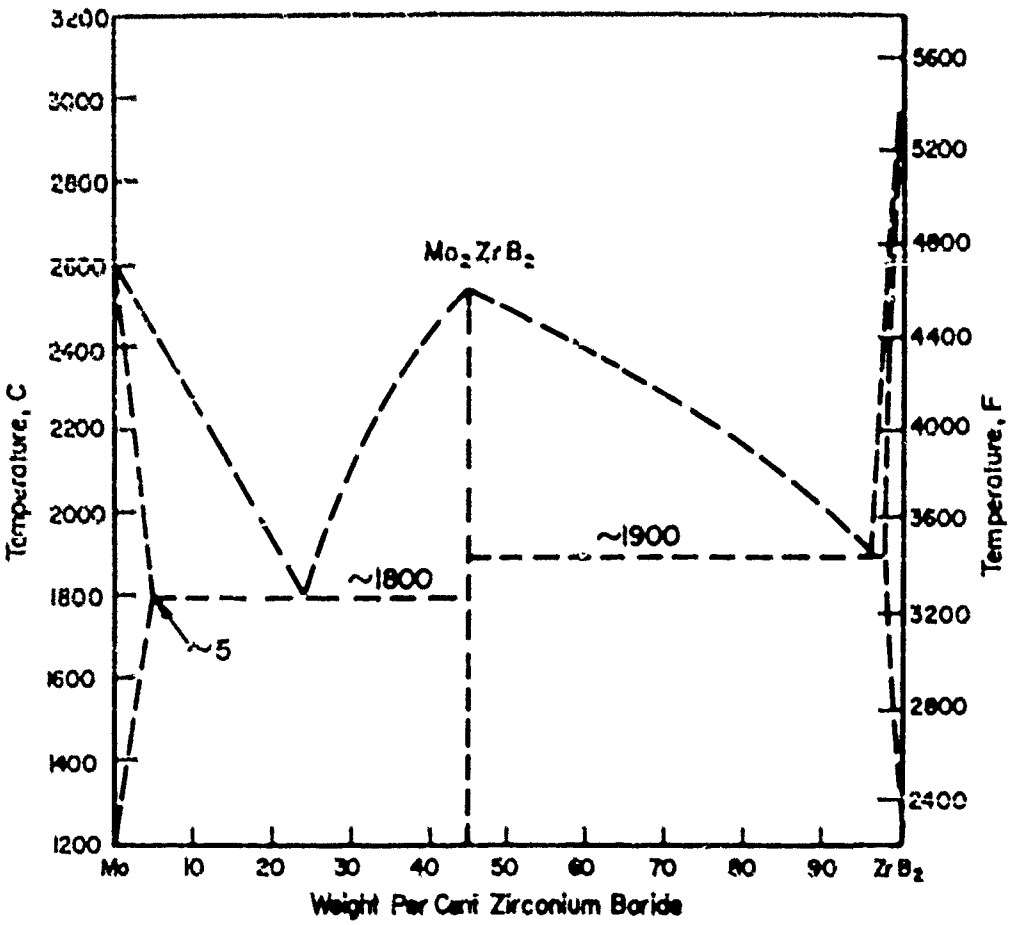
The molybdenum-vanadium system forms a continuous series of solid solutions. The lattice parameters shown were determined by Pepitz and Kieffer.[107]

MOLYBDENUM-ZIRCONIUM SYSTEM

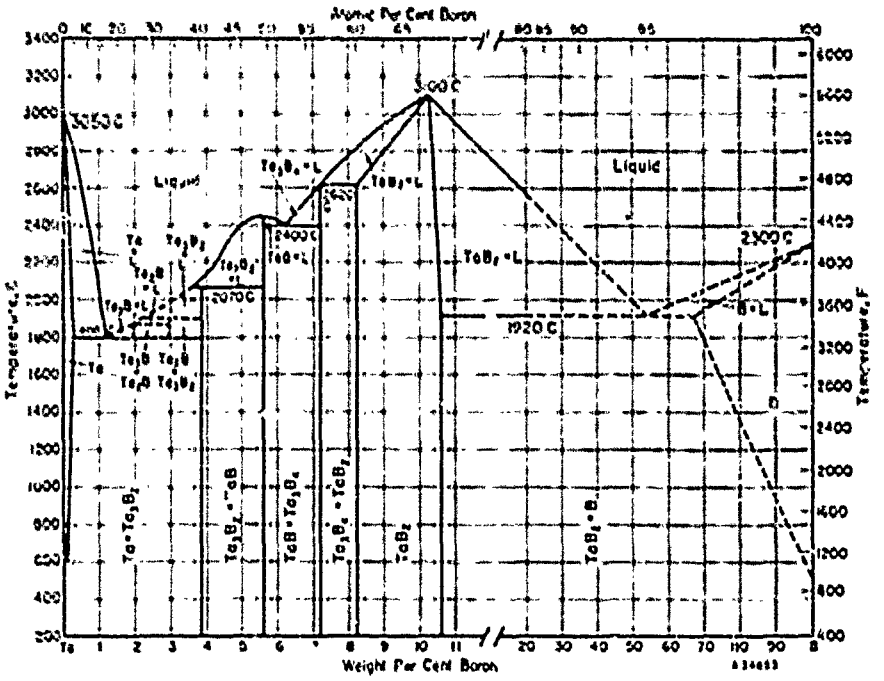


$MoZr_2$ is isotypic with $MgCu_2$ (C15 type), a = 7.596.[107, 111] The solid solubility limit of zirconium in slowly cooled alloys was approximately 7 weight per cent zirconium.[107]

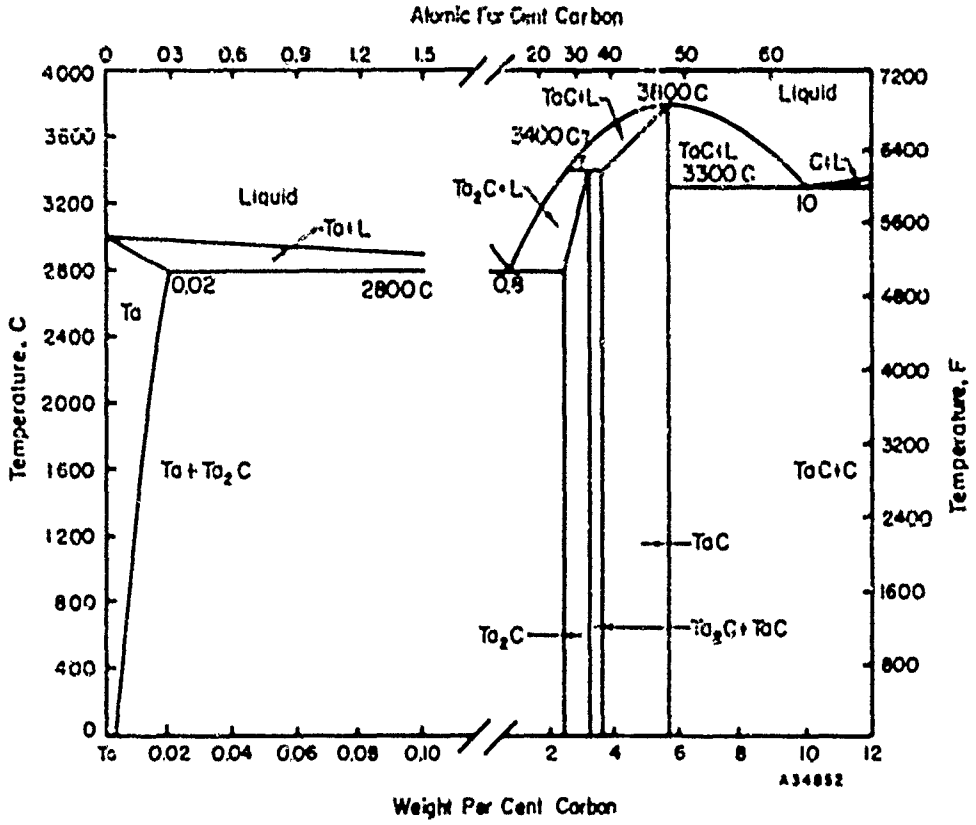
MOLYBDENUM-ZIRCONIUM BORIDE SYSTEM



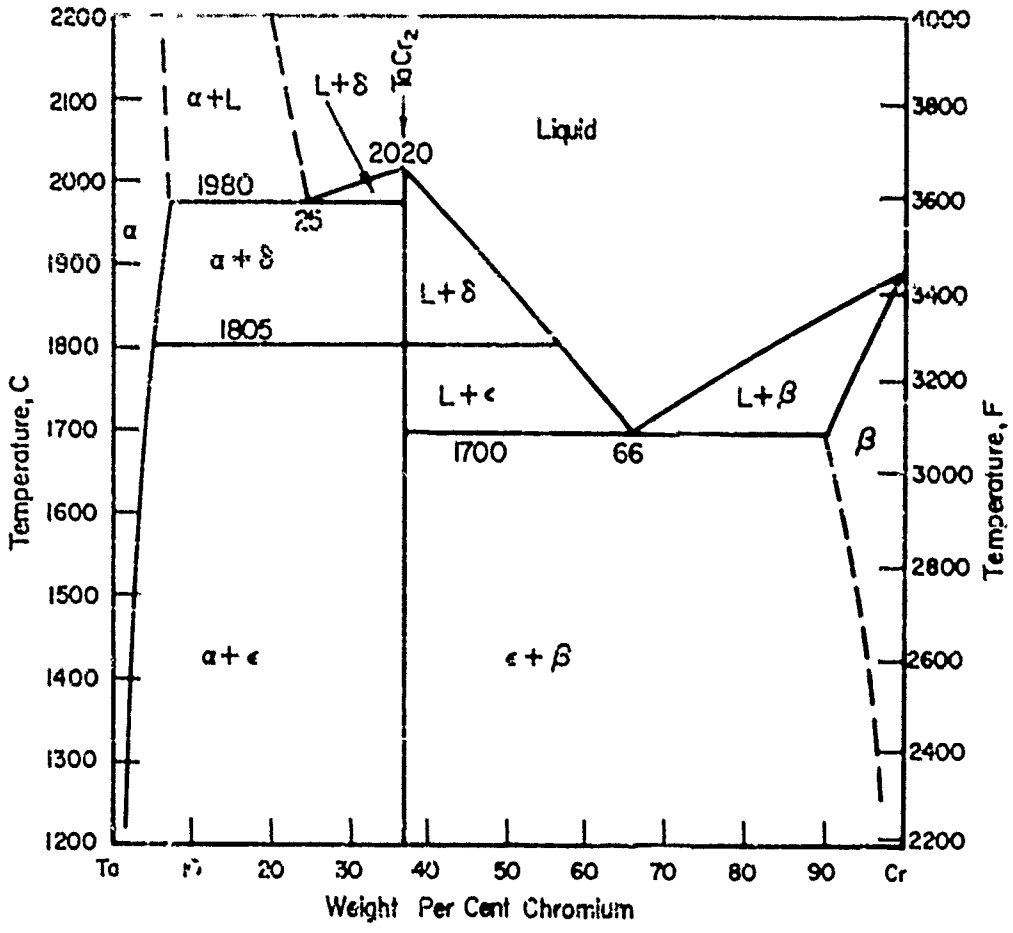
Alloys of 45 weight per cent ZrB_2 (40 atomic per cent) were almost all single phase, Mo_2ZrB_2. The phase has a rhombic structure analogous to Mo_2NiB_2. No other phases were found in the system. At temperatures up to 1800 C, samples containing 24 weight per cent ZrB_2 (20 atomic per cent) melted partially. Alloys with high ZrB_2 content showed signs of melting from 1900 to 2000 C. The maximum solubility of ZrB_2 in molybdenum is about 5 weight per cent. The solubility of molybdenum in ZrB_2 was not determined.(228)



Ta_3B_2 and Ta_3B are stable at high temperatures only.[112] Ta_3B_4 is orthorhombic with a = 3.29 A, b = 14.0 A, and c = 3.13 A.[113] TaB_2 is hexagonal (AlB_2 type) with a = 3.078 A, c = 3.285 A, and c/a = 1.06.[113] Ta_2B has a tetragonal $CuAl_2$-type structure with a = 5.778 A, c = 4.864 A, and c/a = 0.842.[112, 113] TaB is orthorhombic (AB type) with a = 3.29 A, b = 14.0 A, and c = 3.13 A.[113] The phase diagram was developed by Kieffer and Benesovsky.[114]

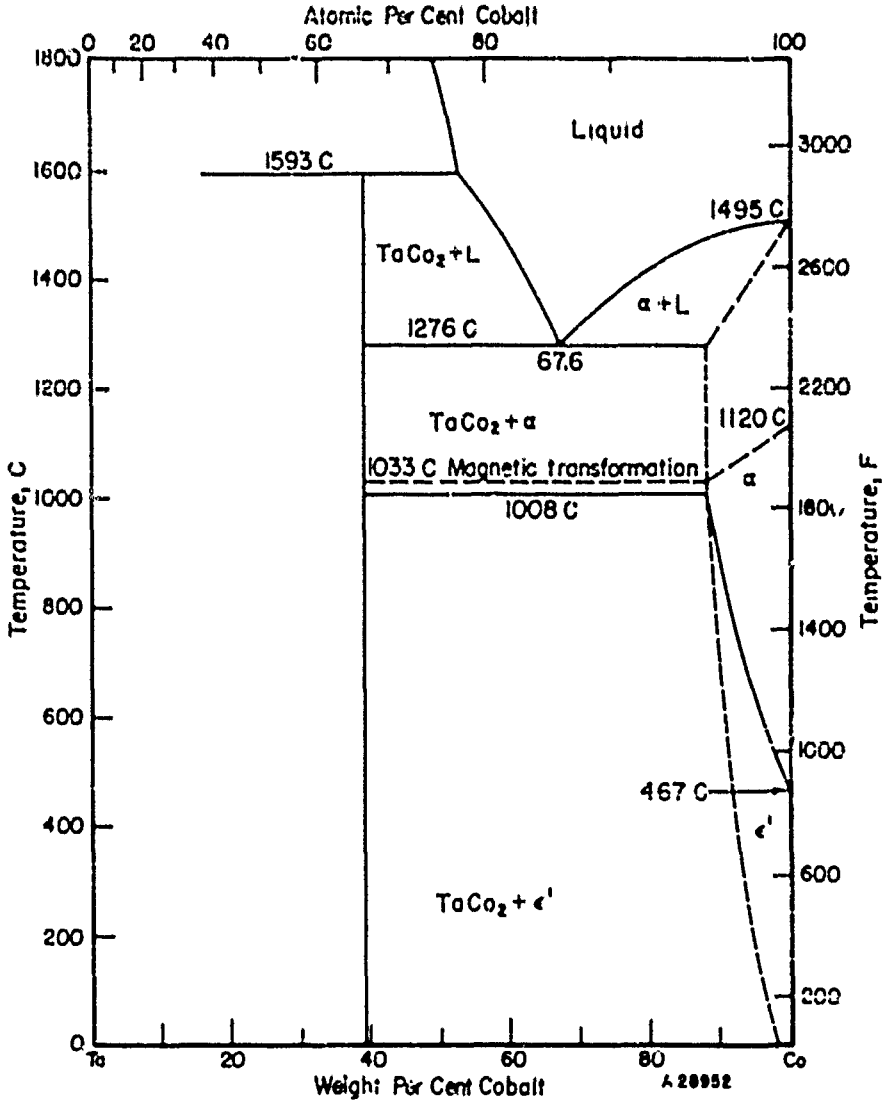


Ta_2C is hexagonal close packed with a = 3.101 to 3.104 A, c = 4.937 to 4.941 A, and c/a = 1.597.[115] TaC is face-centered cubic (NaCl type) with a = 4.20 to 4.67 A.[115] The Ta-Ta_2C eutectic occurs at 0.8 weight per cent carbon and 2600 C, and the TaC-C eutectic occurs at 10 weight per cent carbon and 3300 C.[116-118]



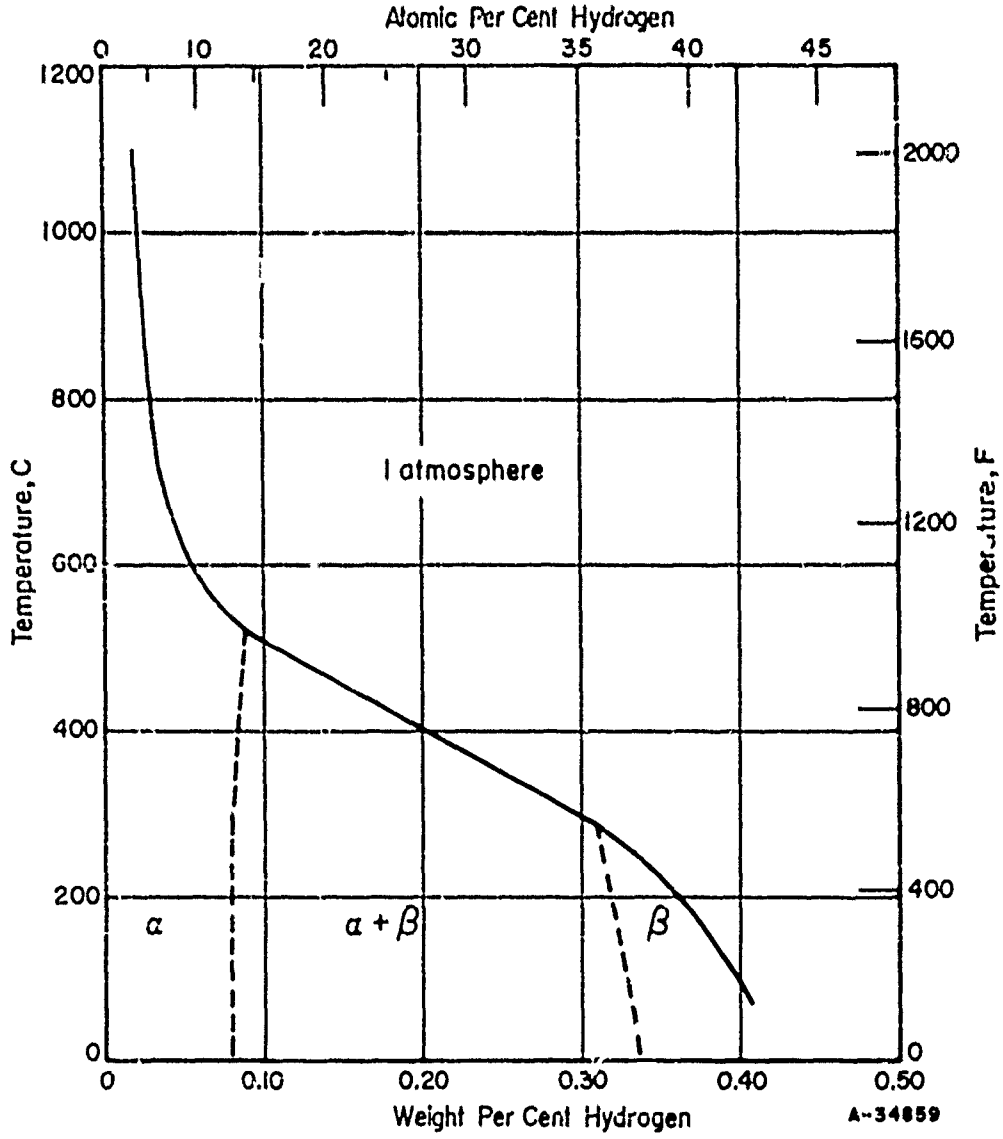
Duwez and Martens[123] reported that $TaCr_2$ has a polymorphic transformation between 1375 and 1650 C from the low-temperature cubic structure ($MgCu_2$-type with a = 6.961 A) to the high-temperature hexagonal structure (a = 4.925 A, c = 8.062 A, c/a = 1.637). Elliott considers the compound isomorphous with $MgZn_2$ at all temperatures from 600 to 1200 C.[124] Grigor'ev et al.[233] states that $TaCr_2$ undergoes a polymorphic transformation at 1805 C. They report that the solubility of chromium in tantalum is about 5 weight per cent at 1800 C, and the solubility of tantalum in chromium is about 10 weight per cent at 1700 C.

TANTALUM-COBALT SYSTEM

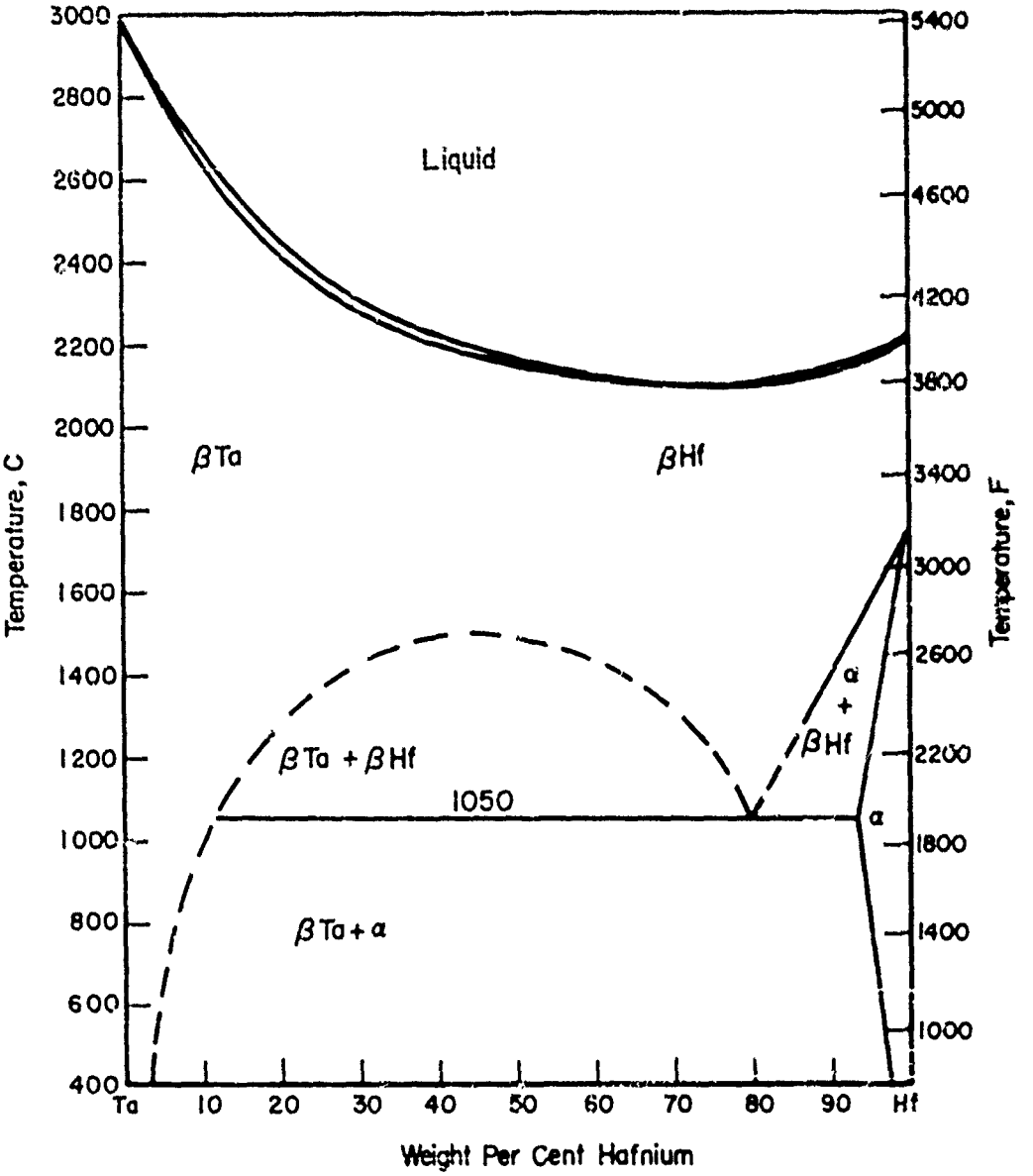


Two modifications of $TaCo_2$ have been reported: the $MgCu_2$ type with a = 6.73 A, and the hexagonal $MgZn_2$ type with a = 4.79 A, c = 7.83 A, and c/a = 1.63.[119] The compound $Ta_{0.8}Co_{2.2}$ (52.7 weight per cent tantalum) possibly occurs between 1000 and 1300 C. Wallbaum[120] identified the phase as a hexagonal, MgN_2-type structure with a = 4.72 A, c = 15.39 A, and c/a = 3.26. Two modifications of the compound $TaCo_3$ (50.6 weight per cent tantalum) were studied by Korchynsky and Fountain: the ordered face-centered cubic with a = 3.65 A, and the hexagonal with a = 9.41 A, c = 15.50 A, and c/a = 1.65.[119] The diagram was determined by Köster and Mulfinger[121] and by Hoschimoto[122].

TANTALUM-HYDROGEN SYSTEM

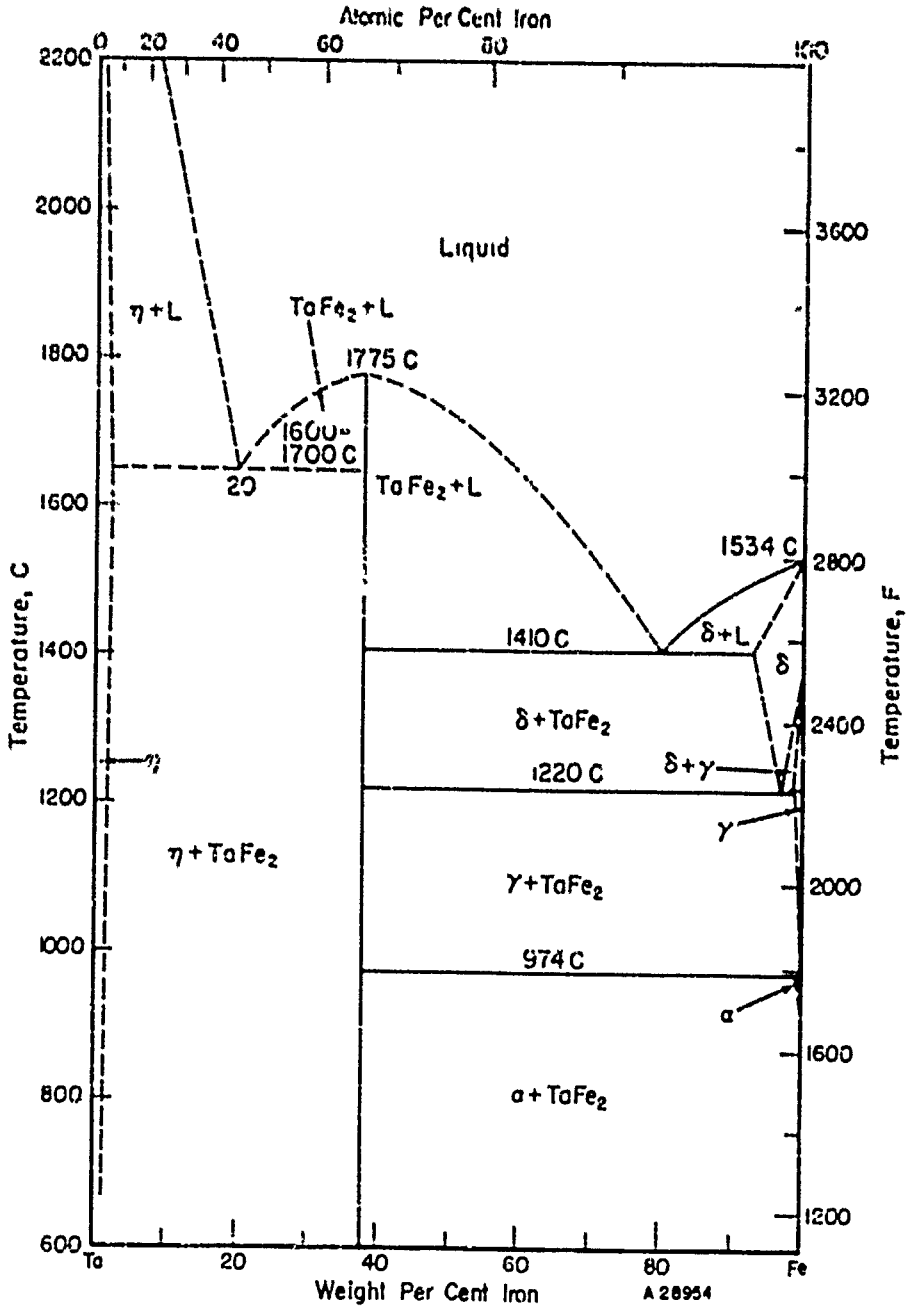


There is poor agreement as to the maximum solubility of hydrogen in tantalum.[126-129] Waite et al. list the solubility of hydrogen as 40 atomic per cent above 50 C, decreasing to 10 and 0 per cent at 0 and -145 C.[130] This strongly temperature-dependent solubility reported by Waite could account for the poor agreement. The second solid solution (β) is body-centered (or slightly distorted body-centered) cubic.[131] The β-phase also has been reported as a hydride of the approximate composition Ta_2H with a body-centered tetragonal structure gradually distorting to a face-centered orthorhombic structure.[130]



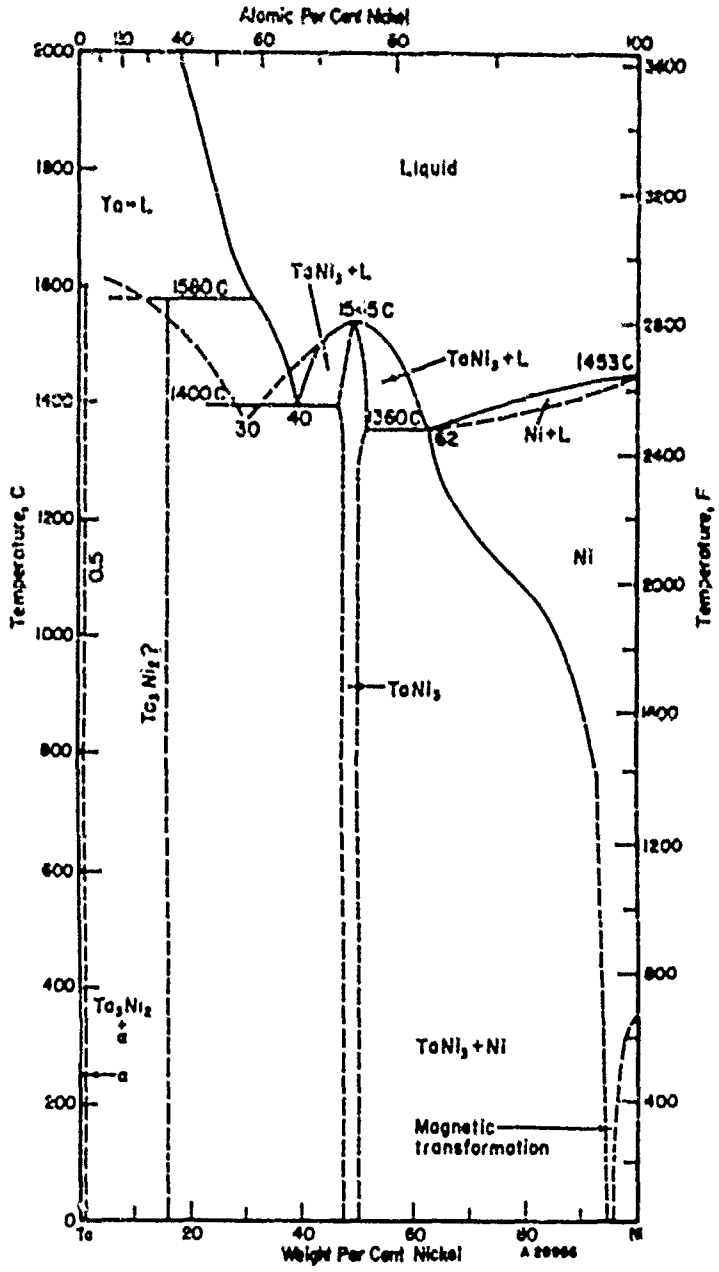
Melting-point determinations for the tentative diagram determined by Deardorff[232] were made between 50 and 100 weight per cent hafnium. The results indicated a minimum melting point near 80 weight per cent hafnium. The eutectoid temperature is 1050 C with the eutectoid composition about 80 weight per cent hafnium. The solubility of tantalum in hafnium is about 7 weight per cent at 1050 C, possibly decreasing to less than 0.30 weight per cent at 950 C.

TANTALUM-IRON SYSTEM

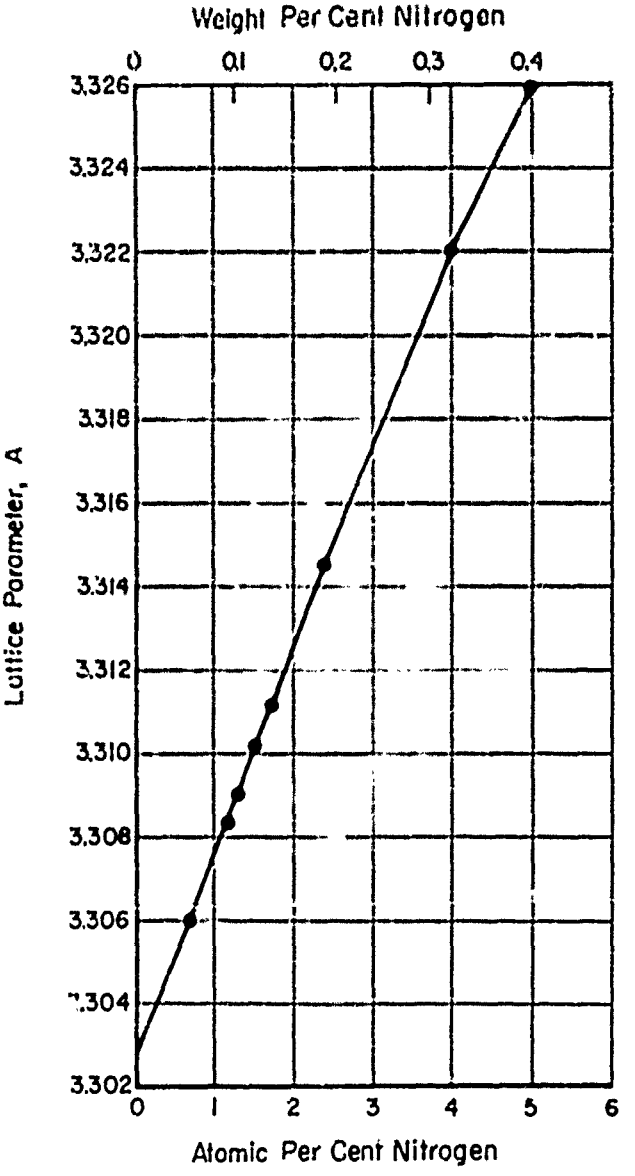


$TaFe_2$ has the $MgZn_2$ (C14) type of structure with a = 4.81 A, c = 7.85 A, and c/a = 1.63.[120]
The diagram was developed by Genders and Harrison.[125]

TANTALUM-NICKEL SYSTEM

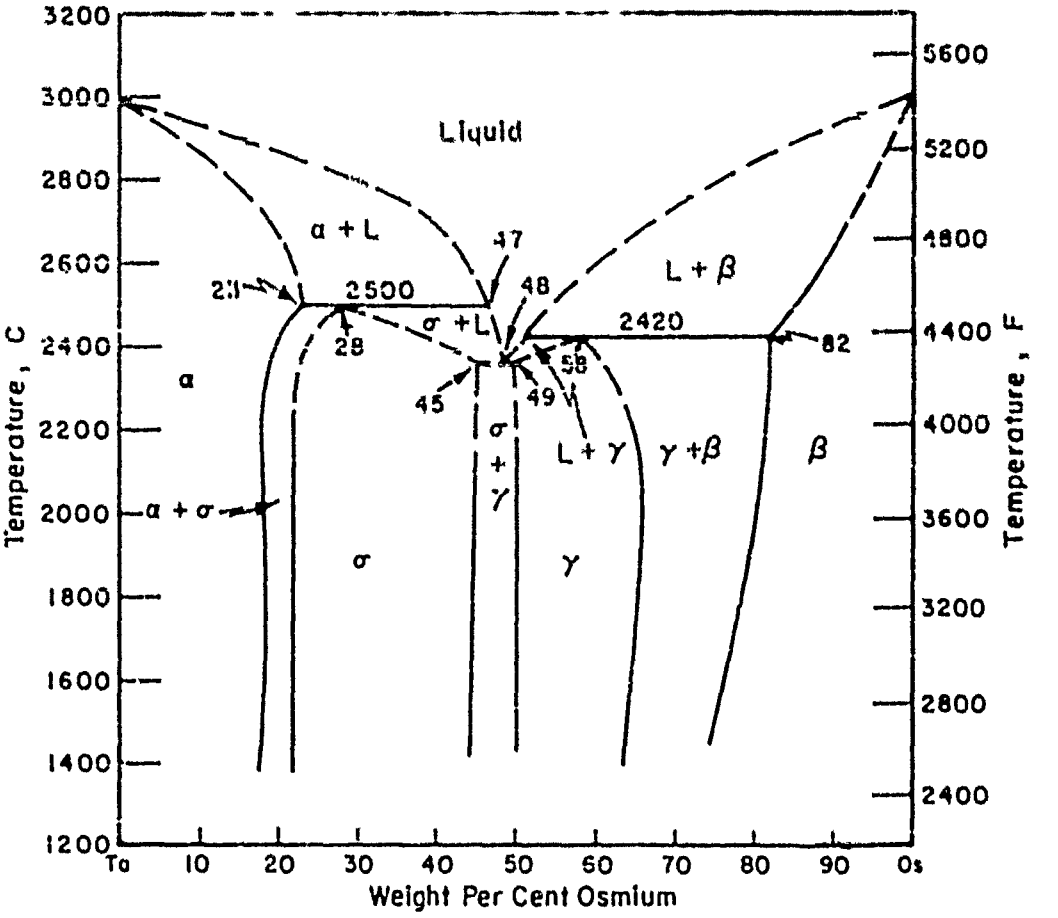


$TaNi_3$ is orthorhombic (slightly deformed hcp) with a = 5.114 A, b = 4.250 A, and c = 4.542 A.[136] The compound Ta_3Ni_2 has been reported but not confirmed.[139] Alloys between 0 and 5 weight per cent nickel and below 1600 C consist of a tantalum-rich solid solution containing less than 0.05 weight per cent nickel and an intermediate phase.[140]

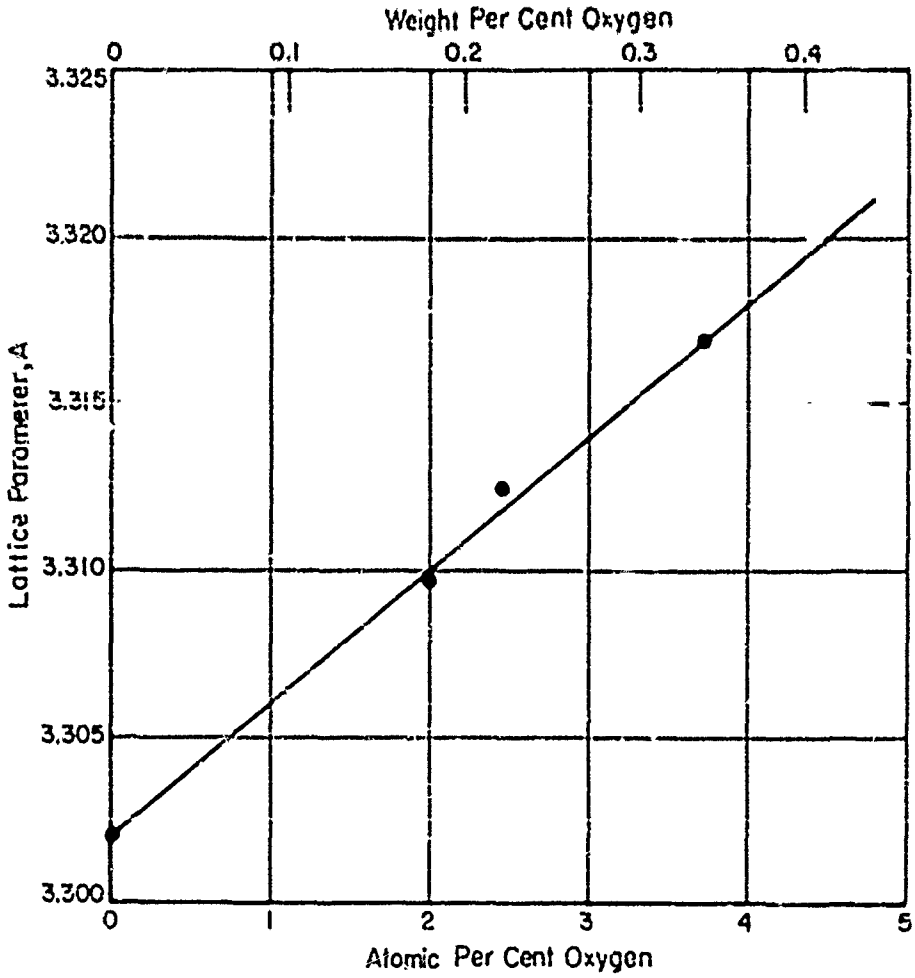


Two intermetallic compounds are definitely established for the tantalum-nitrogen system. TaN is hexagonal close packed with a = 5.181 kX, c = 2.905 kX, and c/a = 0.561.[132] Ta_2N is also hexagonal close packed with a = 3.042 kX, c = 4.909 kX, and c/a = 1.614.[132, 133] The melting point of TaN has been given as 2850 C[134] and 3090 C[135]. Chiotti has shown that TaN dissociates at high temperatures, forming the lower nitride, Ta_2N, and nitrogen.[136] Between 1600 and 2000 C, at least 7 atomic per cent nitrogen dissolves in tantalum.[137]

TANTALUM-OSMIUM SYSTEM

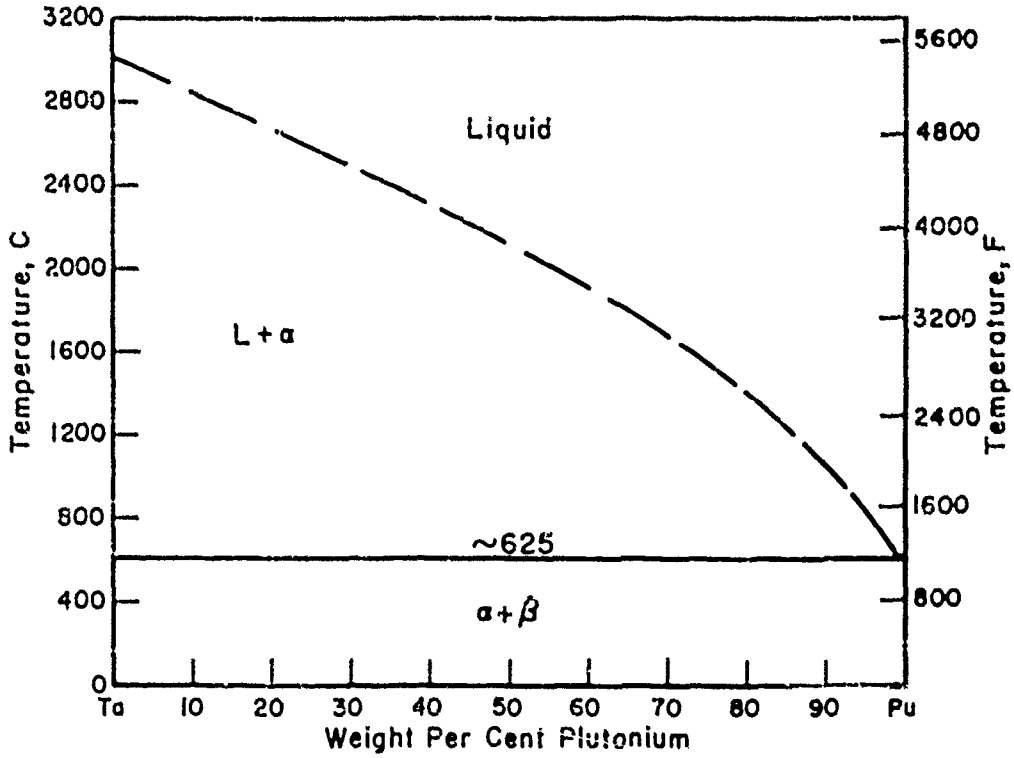


The sigma phase forms by a peritectic reaction at approximately 2500 C.[147] The structure is tetragonal with a = 9.934 A and c = 5.189 A at 26 weight per cent (25 atomic per cent) osmium.[148] The gamma phase forms by a peritectic reaction at 2420 C.[147] The structure is probably the cubic α-manganese type observed by Knapton[34], with the lattice parameter a = 3.639 A. The solubility of osmium in tantalum is 16 weight per cent (15 atomic per cent) at 1600 C, increasing to 23 weight per cent (22 atomic per cent) at 2500 C.[147] The solubility of tantalum in osmium is 26 weight per cent (25 atomic per cent) at 1600 C, decreasing to 18 weight per cent (19 atomic per cent) at 2420 C.[147]

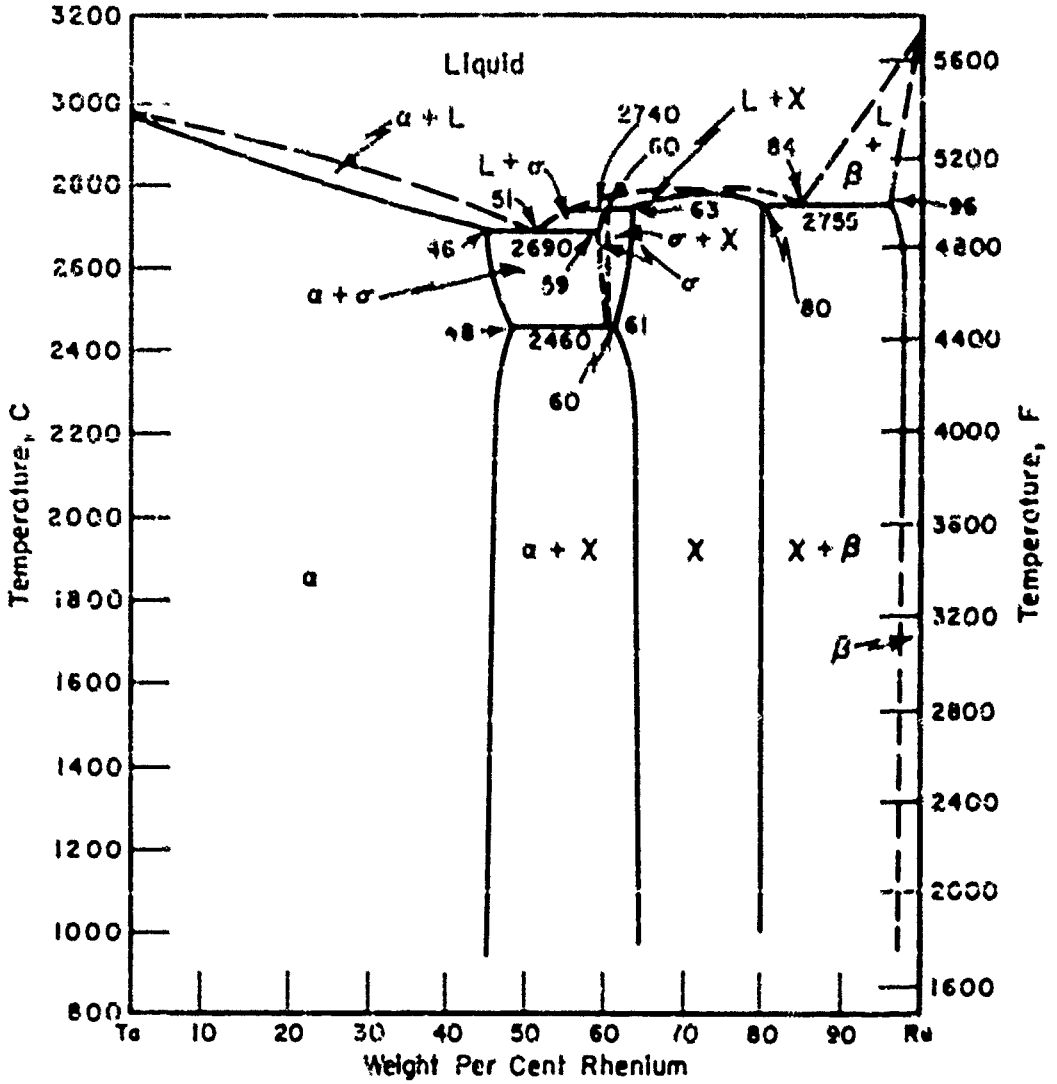


Six oxides of tantalum have been reported. β-Ta_2O_5 is the only oxide that is firmly established. It has an orthorhombic structure with a = 6.19 A, b = 3.66 A, and c = 3.89 A.(141) β-Ta_2O_5 transforms to the high-temperature α-Ta_2O_5 at 1320 to 1350 C.(142,143) TaO_2 has a tetragonal (TiO_2 type) structure with a = 4.709 A, c = 3.065 A, and c/a = 0.651.(144) TaO is cubic (NaCl type) with a = 4.22 to 4.39 A.(144) Ta_2O is orthorhombic with a = 5.29 A, b = 4.92 A, and c = 3.05 A.(143) Ta_4O is orthorhombic with a = 7.194 to 7.238 A, b = 3.266 to 3.273 A, and c = 3.204 to 3.216 A.(144) The solid solubility of oxygen in tantalum is 1.5, 2.2, 3.1, and 4.2 atomic per cent at 700, 900, 1100, and 1300 C, respectively.(145) The lattice parameters were determined by Gebhardt.(146)

TANTALUM-PLUTONIUM SYSTEM

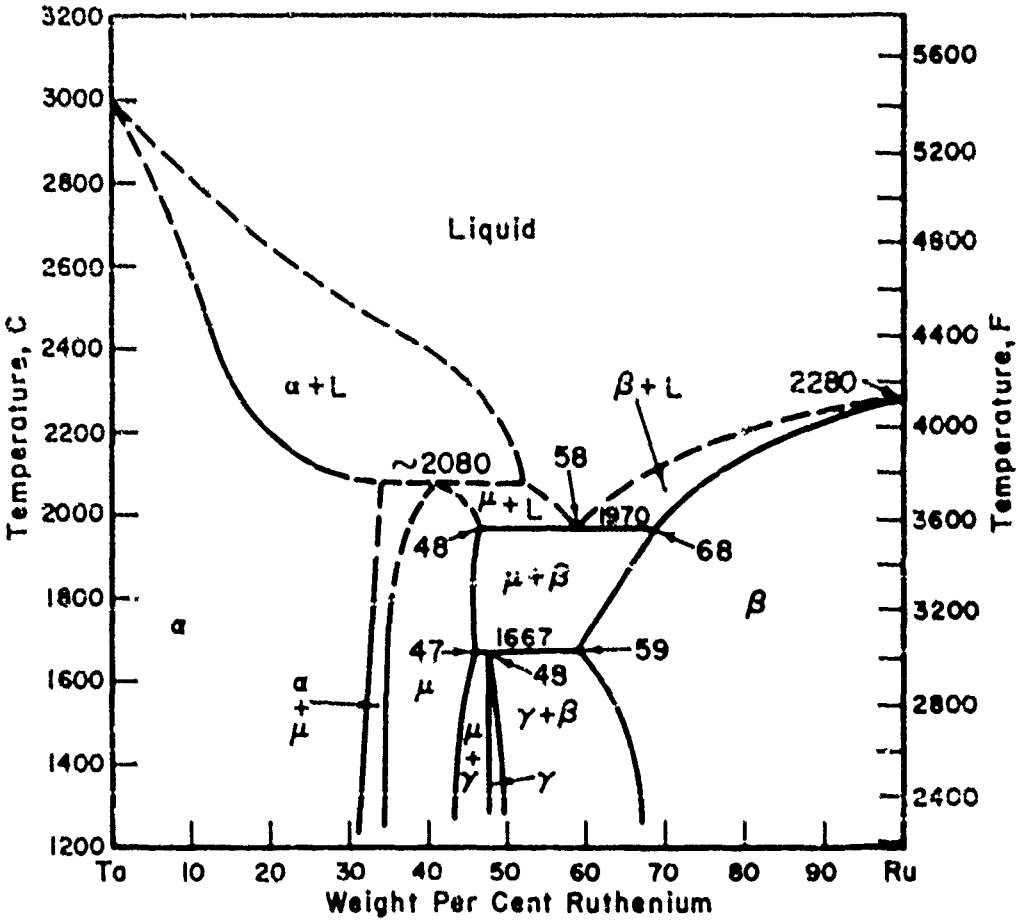


No intermediate phases are known to exist in this system.



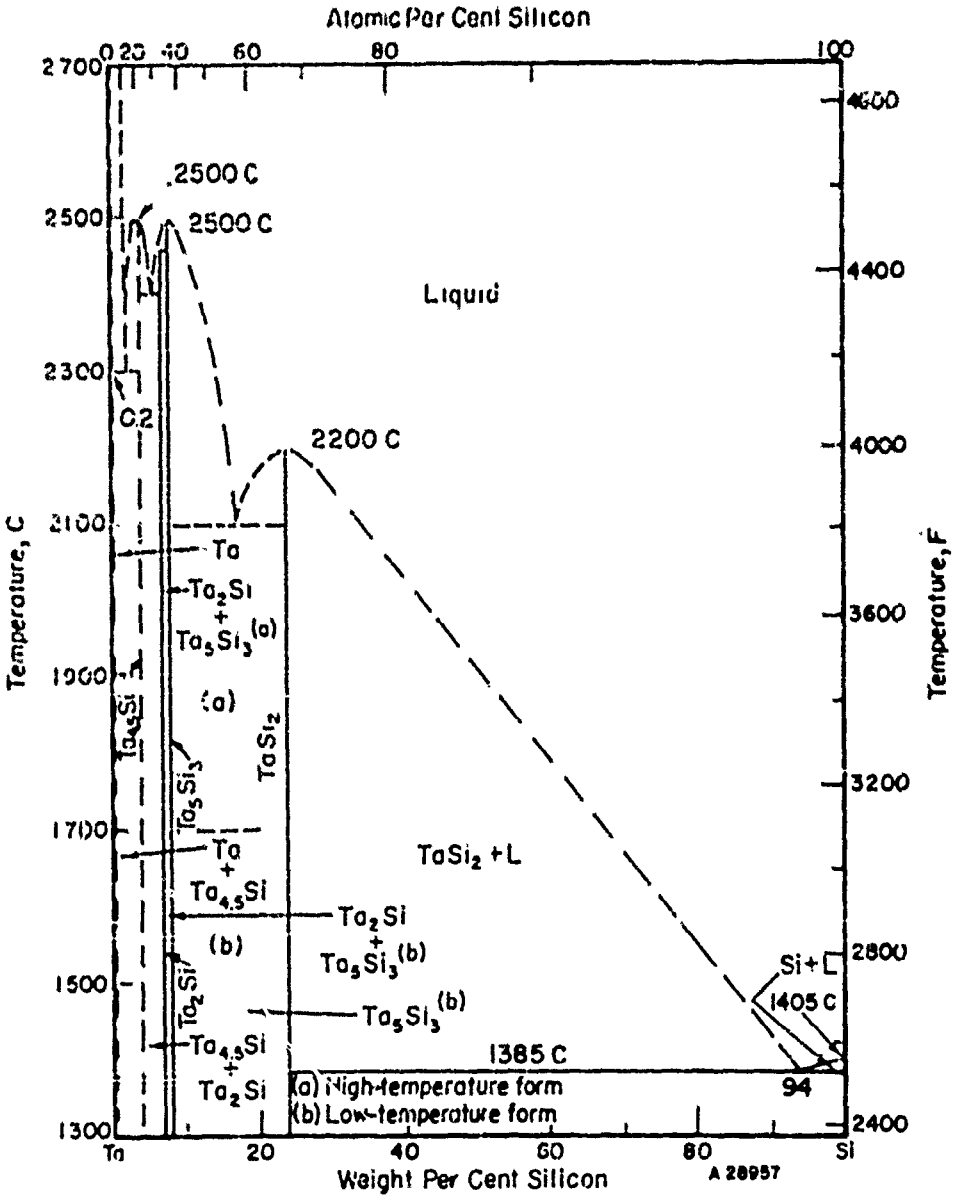
Re_3Ta_2, the sigma phase, has a complex tetrahedral structure, isomorphous with the sigma phase found in the iron-chromium system. The lattice parameter is a = 9.69 A and c/a = 0.52.[149] The chi phase is a complex cubic, isomorphous with α-manganese. The lattice parameter varies from 9.80 A at 60 weight per cent (69 atomic per cent) to 9.63 A at 80 weight per cent (79 atomic per cent).[149]

TANTALUM-RUTHENIUM SYSTEM

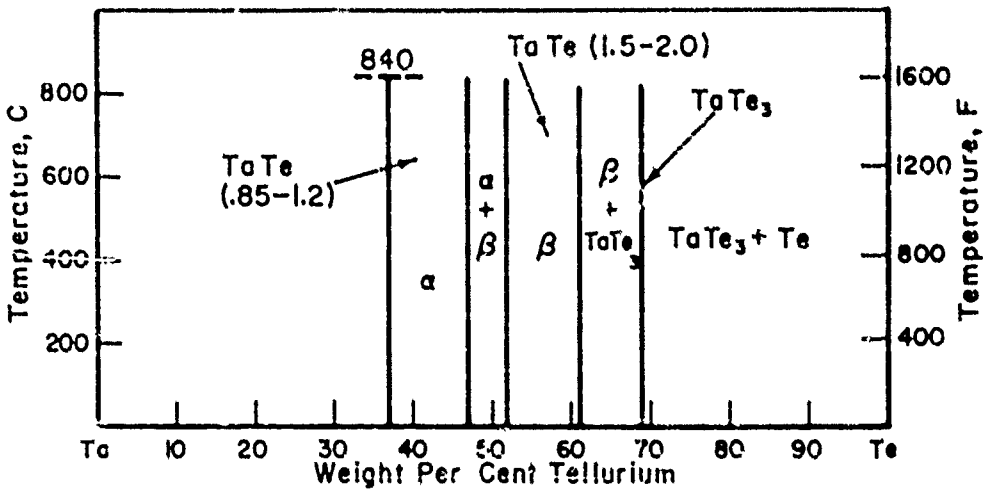


Ruthenium is highly soluble in tantalum, as indicated by the large α field. Detailed X-ray analysis of the α-phase showed that the body-centered cubic structure of tantalum changes to a body-centered tetragonal as the rhenium content increases. This change begins between 24 and 27 weight per cent rhenium (35 and 40 atomic per cent). An ordering reaction in the solid solution near 30 weight per cent rhenium was also indicated. The structures of the intermediate phases μ and γ were not discussed. (147)

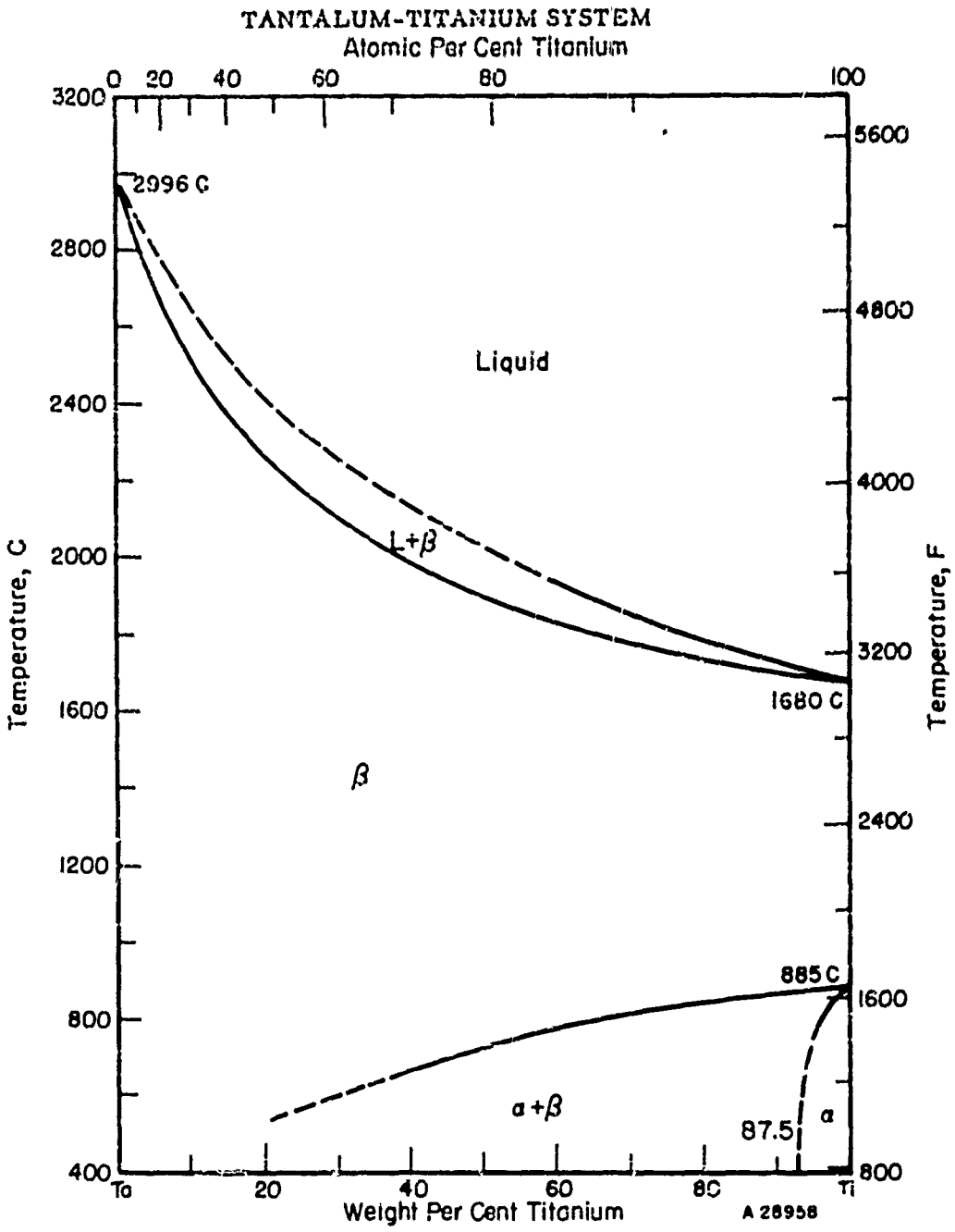
TANTALUM-SILICON SYSTEM



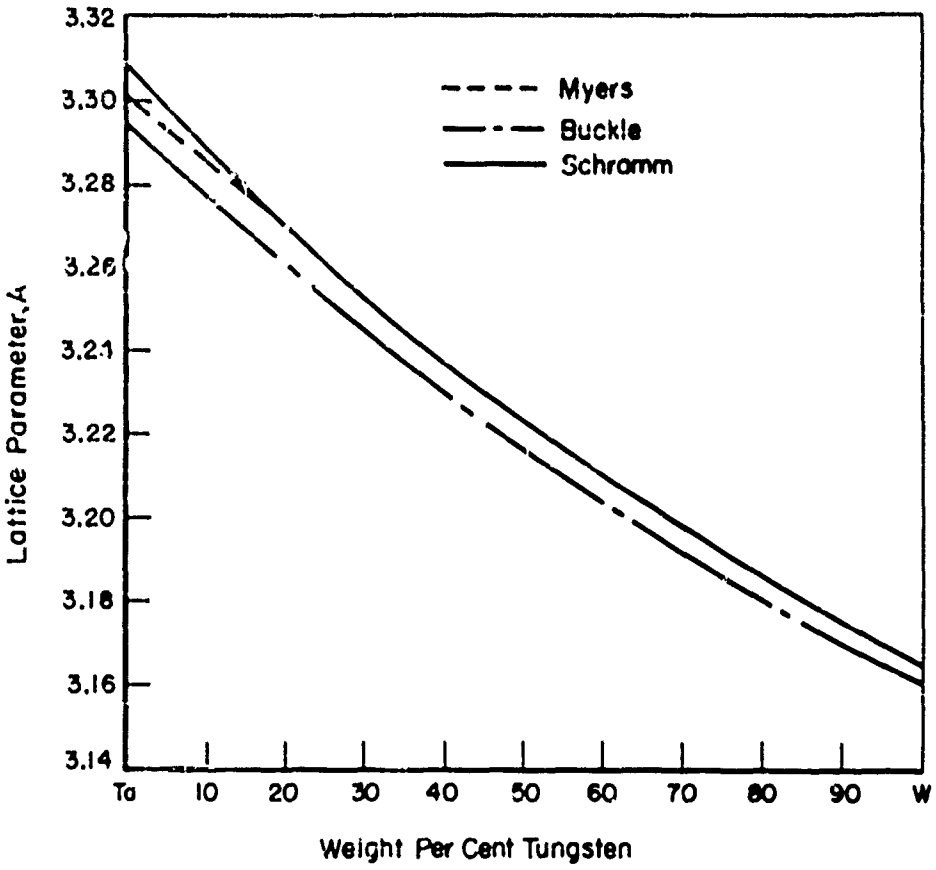
$Ta_{4.5\pm0.5}Si$ is hexagonal (Ni_3Sn type) with a = 6.093 kX, c = 4.909 kX, and c/a = 0.807.[150] Ta_2Si is tetragonal ($CuAl_2$ type) with a = 6.155 kX, c = 5.029 kX, and c/a = 0.818.[150] Ta_5Si_3 is hexagonal (Mn_5Si_3 type) with a = 7.459 kX, c = 5.215 kX, and c/a = 0.699.[150] $TaSi_2$ is hexagonal ($CrSi_2$ type) with a = 4.771 kX, c = 6.551 kX, and c/a = 1.373.[150] Parthé et al.[151] found a high- and low-temperature modification for Ta_5Si_3 with a tetragonal structure and lattice parameters a = 9.96 kX, c = 5.05 kX, c/a = 0.51 and a = 6.503 kX, c = 11.849 kX, and c/a = 1.822, respectively. Hansen[15] proposed the phase diagram shown.



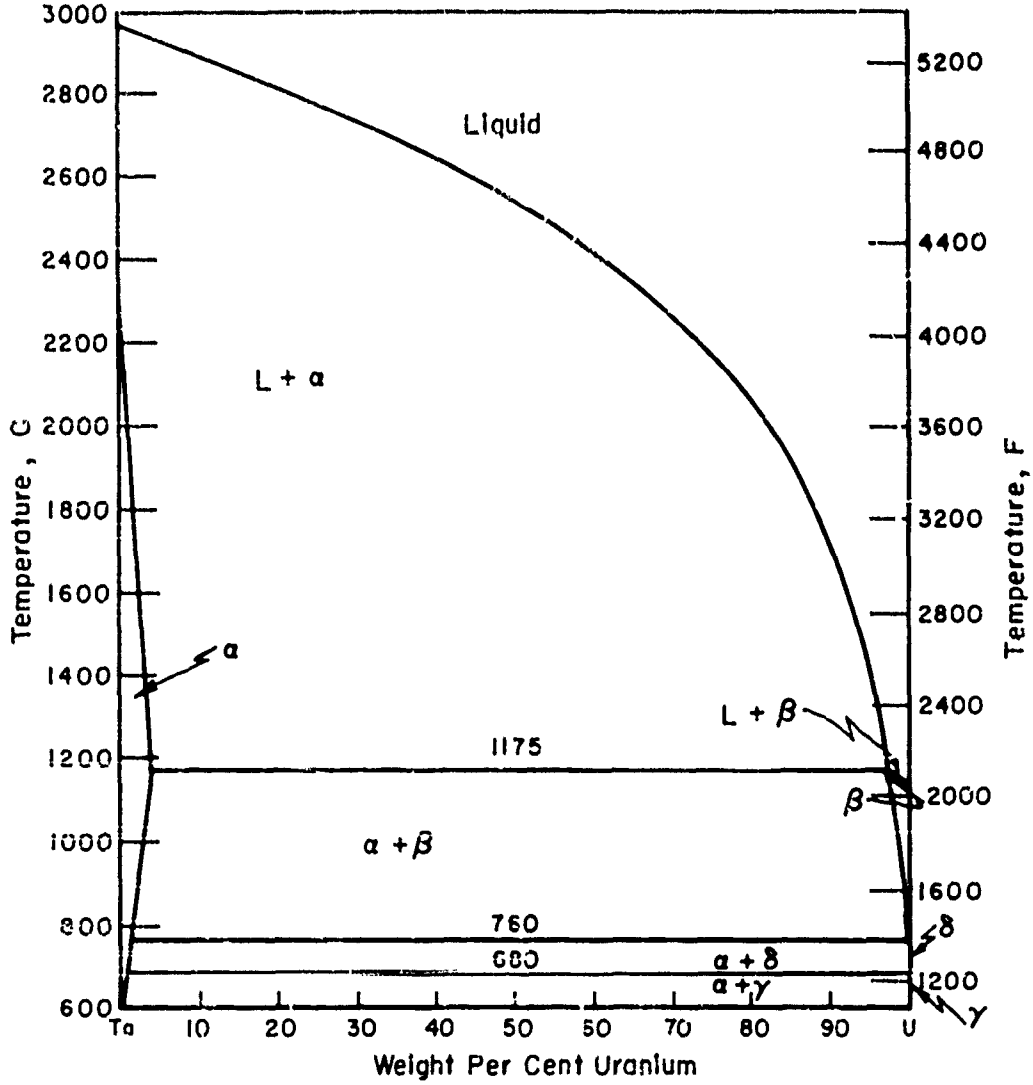
The compound $TaTe_3$ has a tetragonal lattice with a = 6.5 kX and c = 11.8 kX. The α-phase, $TaTe_{0.85-1.2}$, shows a polymorphic change at 840 C. There is also evidence for the existence of a lower telluride of tantalum.[152]



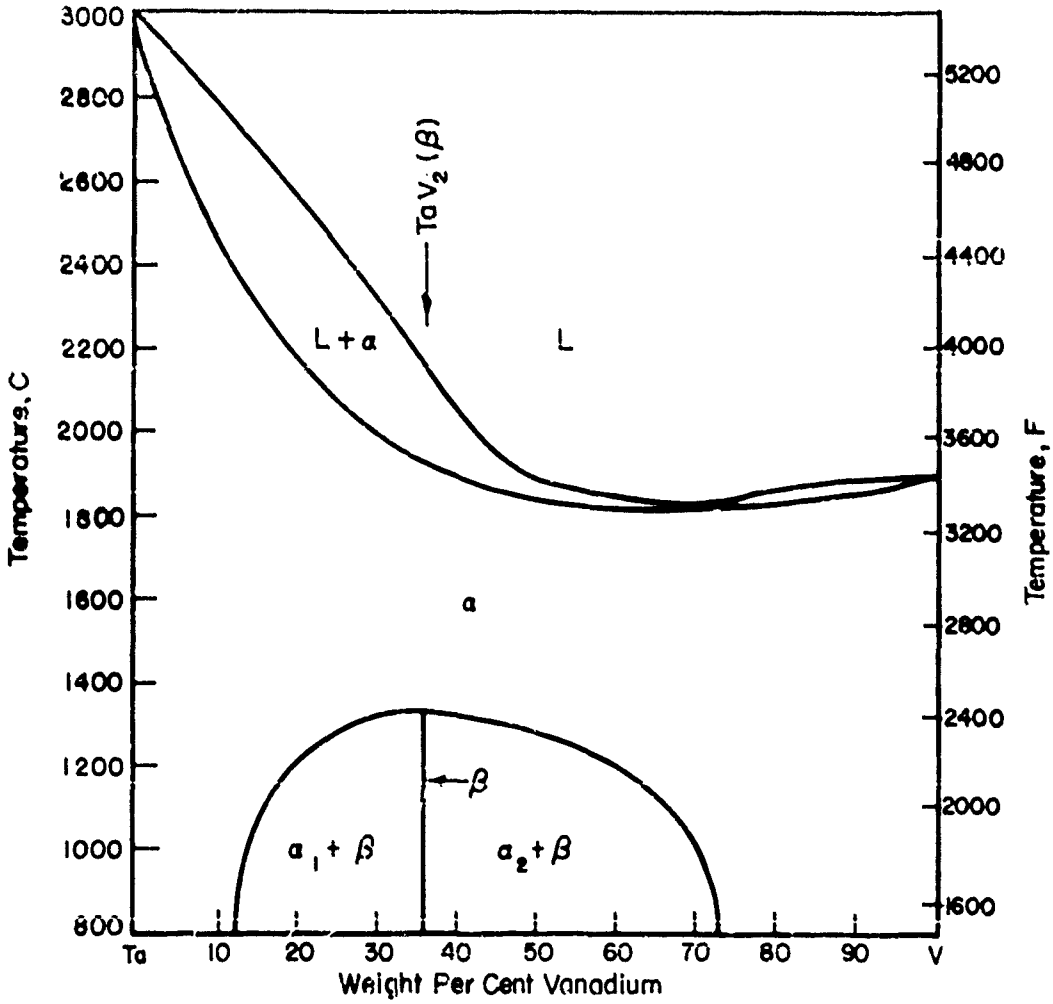
Tantalum and β-titanium form a continuous series of solid solutions. The beta solid solution can be retained on quenching for titanium contents up to 50 to 60 weight per cent. (153, 154)



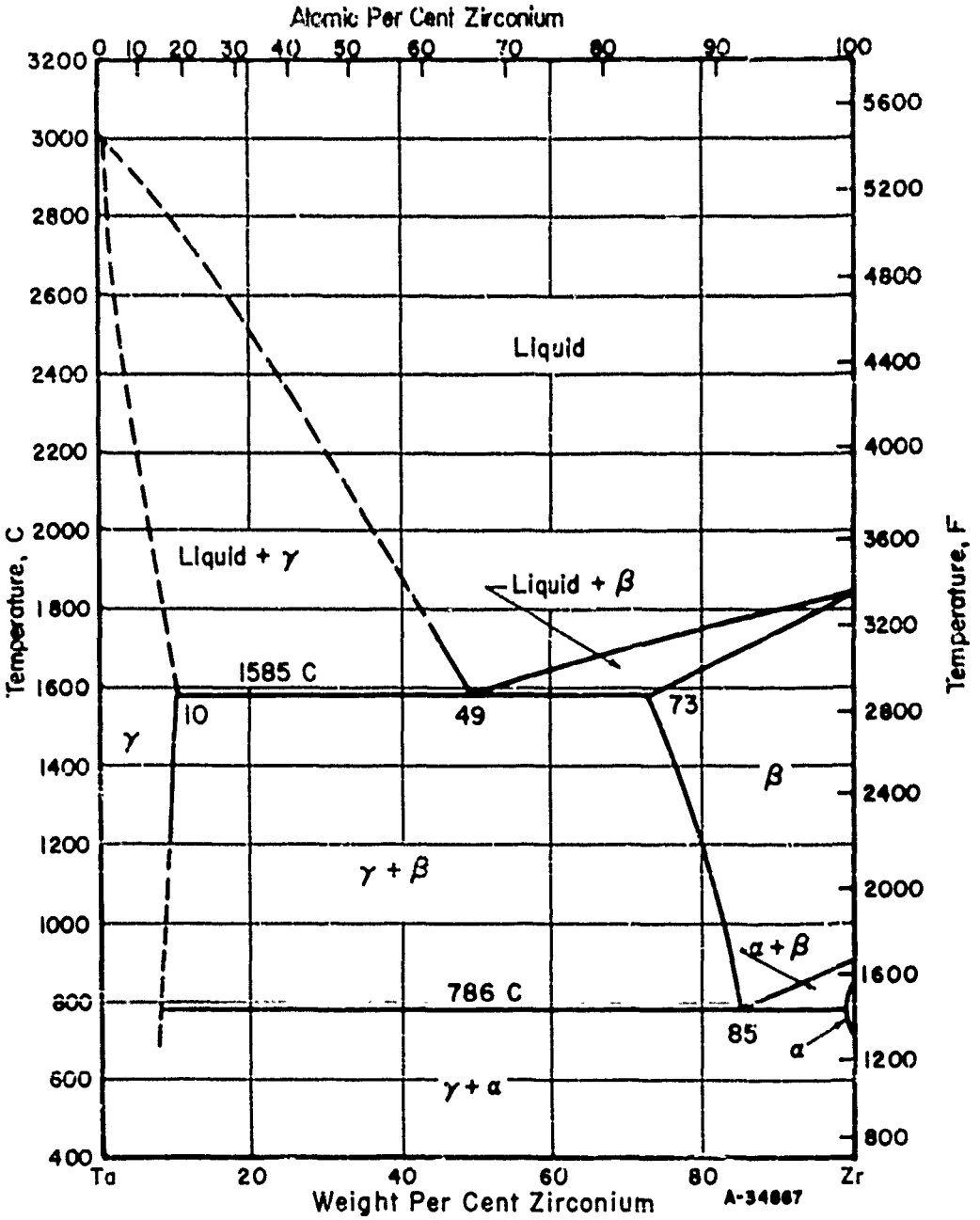
Tantalum and tungsten form a complete series of solid solutions.(40, 155, 158, 159)



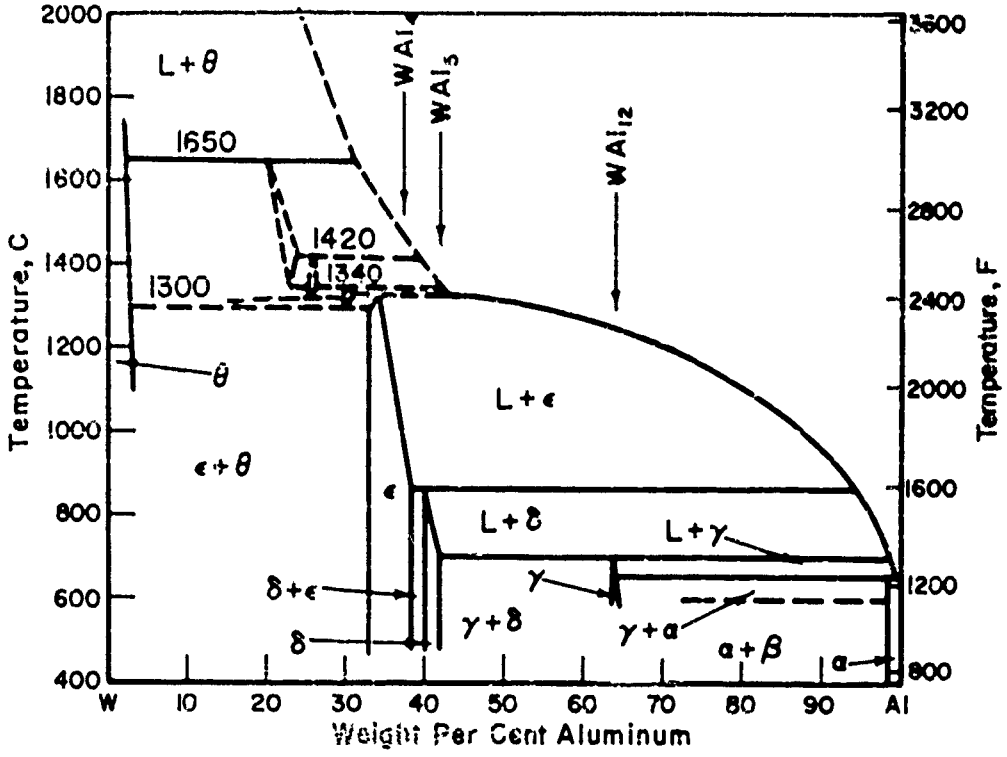
The high-temperature solid solubility of tantalum in uranium and uranium in tantalum is less than 2 atomic per cent. A peritectic reaction occurs at 1175 C near the uranium-rich side. No intermediate compounds were observed.(155)



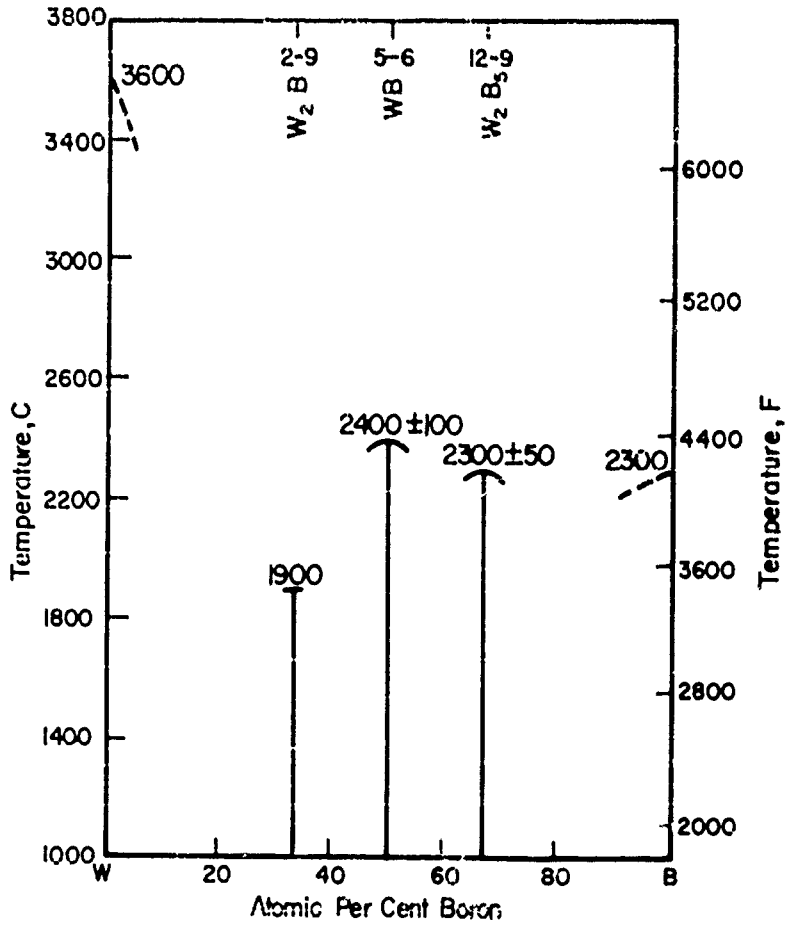
Complete miscibility exists above 1320 C. Below this temperature TaV_2 precipitates. The structure was shown to be face-centered cubic isomorphous with $MgCu_2$.(156, 157)



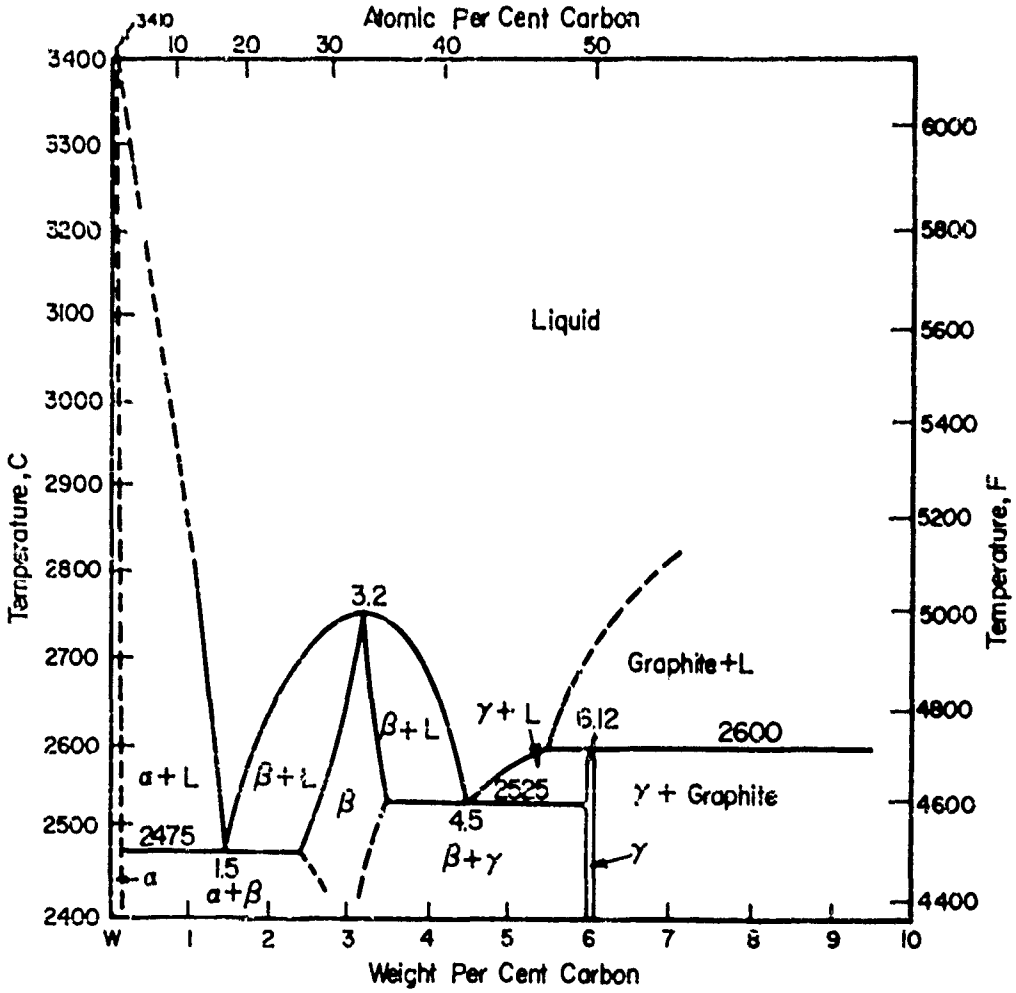
The maximum solubility of zirconium in tantalum is approximately 10 weight per cent. The maximum solubility of tantalum in β-zirconium is approximately 27 weight per cent. The solubility of tantalum in α-zirconium is less than 0.22 atomic per cent. No intermediate phases were found.(160)



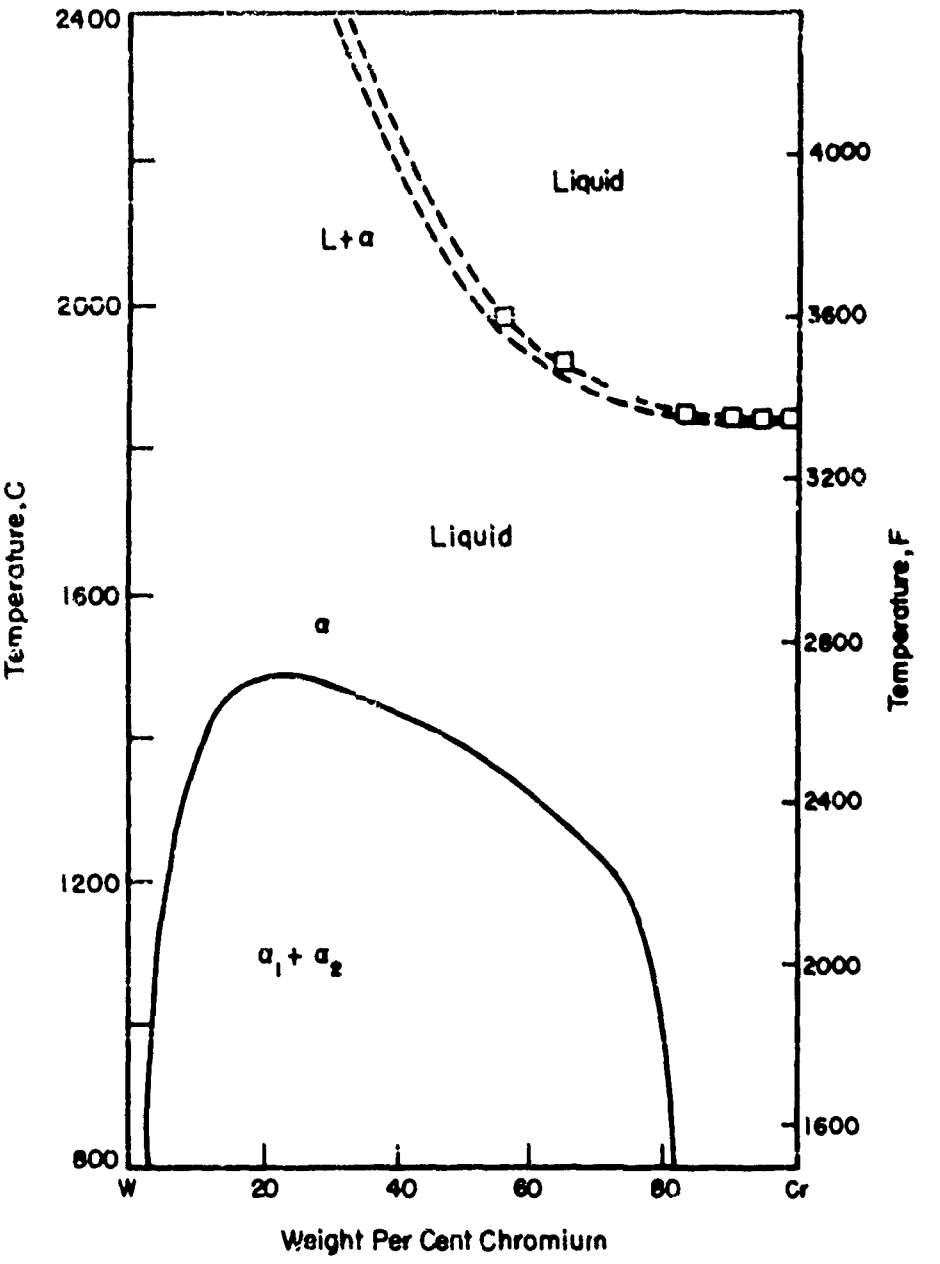
$WAl_4(\epsilon)$ has a monoclinic structure with a = 5.272 A, b = 17.771 A, c = 5.216 A, and $\beta = 100° 12'$. The cell contains 30 atoms mostly confined to 8 well-defined layers.[161] $WAl_{12}(\gamma)$ has a body-centered cubic structure with two WAl_{12} units per cell.[163] The third intermediate phase is $WAl_9(\delta)$. The solubility of aluminum in tungsten is 2.4 weight per cent at 1300 C; the solubility of tungsten in aluminum is 1.5 weight per cent at 650 C.[162]



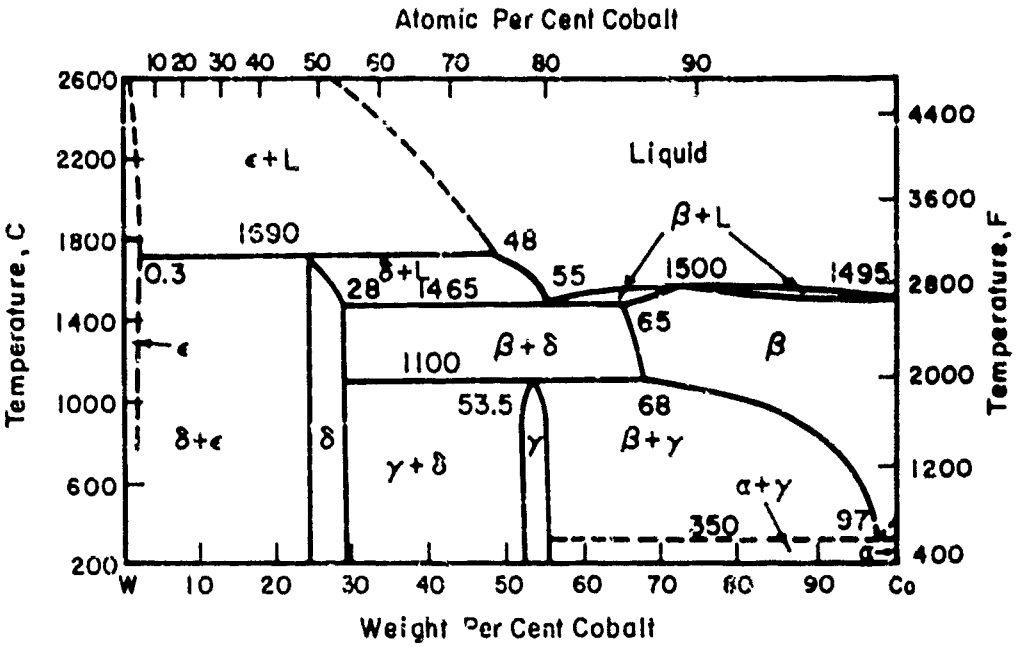
W_2B is tetragonal of the $CuAl_2$ (C16) type with a = 5.564 A, c = 4.740 A, and c/a = 0.852.[58] A low-temperature form of WB, stable below 1850 C, is tetragonal (MoB type) with a = 3.115 A, c = 16.93 A, and c/a = 5.44.[58] The high-temperature modification, corresponding to β-MoB, is orthorhombic (CrB type) with a = 3.07 A.[164] WB_5 has a hexagonal defect structure with a = 2.962 A, c = 13.87 A, and c/a = 4.65.[164] The phase diagram was obtained from Reference 108.



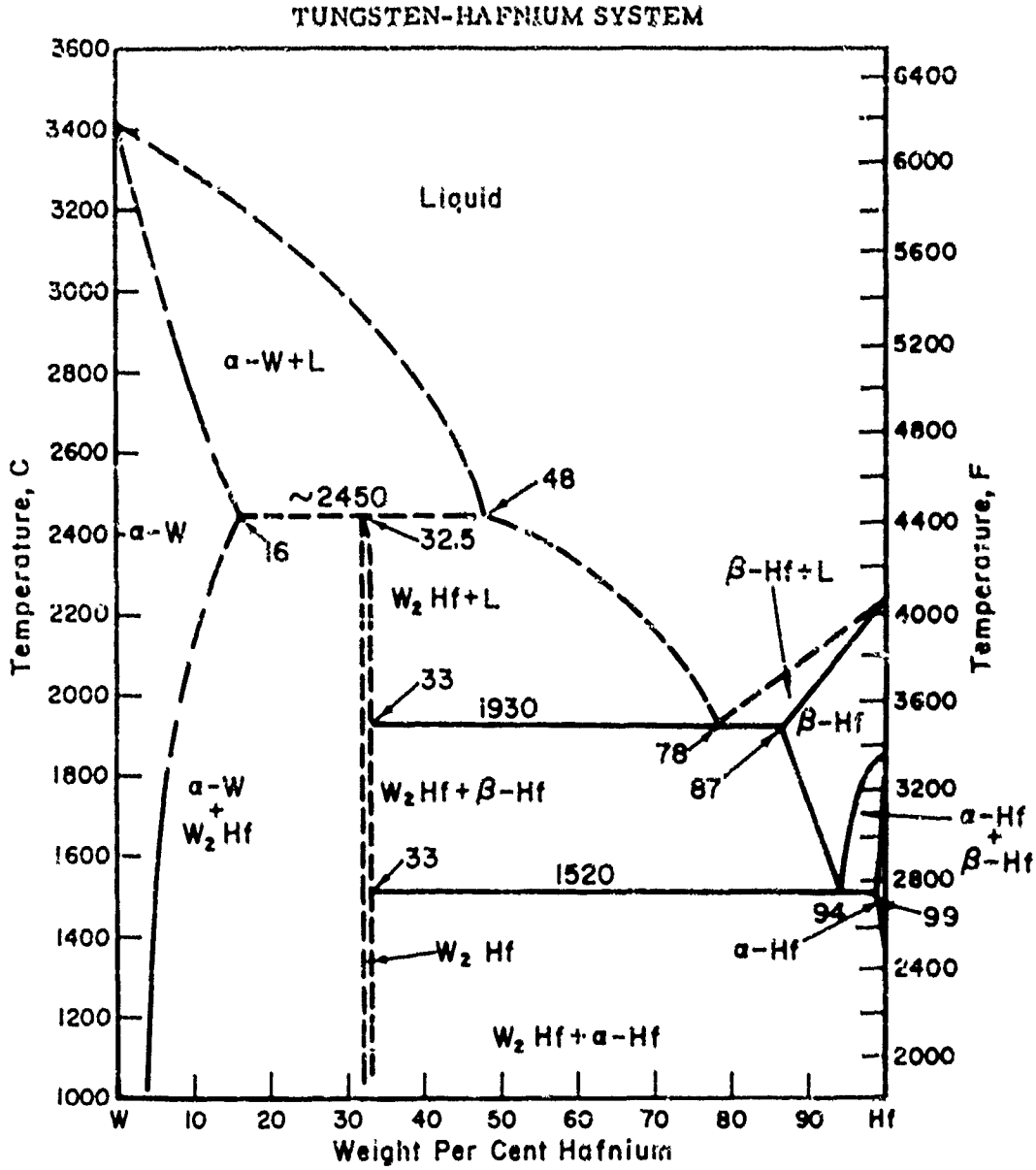
The low-temperature modification of W_2C is hexagonal with a = 2.994 A, c = 4.724 A, and c/a = 1.578.(165) The high-temperature modification β-W_2C is possibly a face-centered cubic structure with a = 4.16 A.(166) WC has a simple hexagonal structure with a = 2.906 A, c = 2.83 A, and c/a = 0.976.(165)



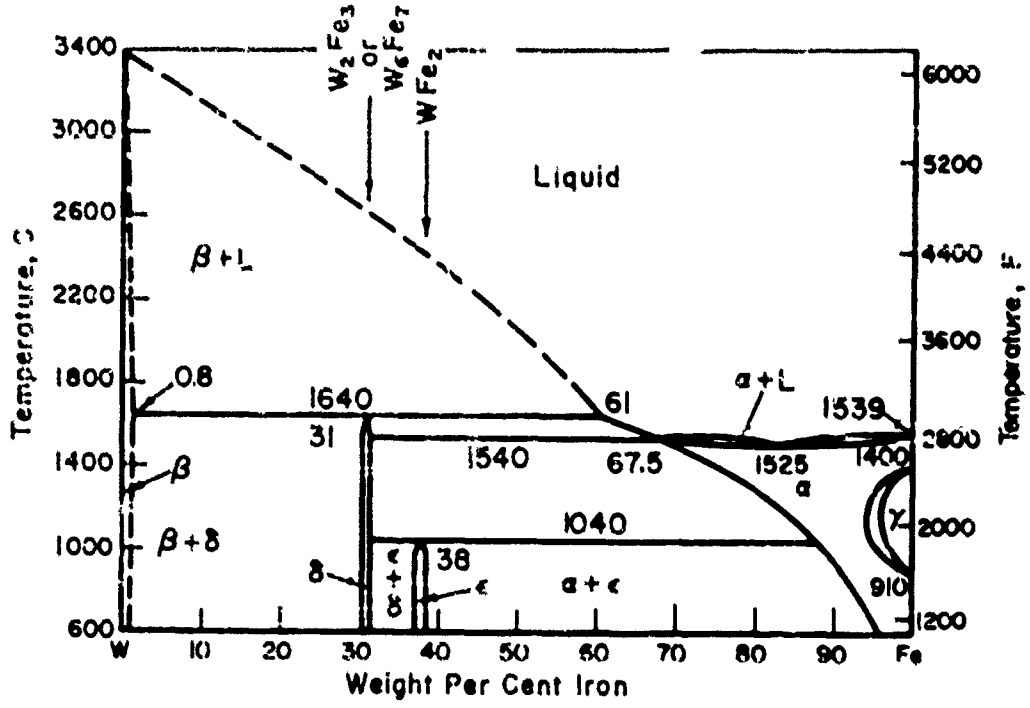
Tungsten and chromium form a continuous series of solid solutions above 1800 C. A solid-state immiscibility field exists below this temperature.[171]



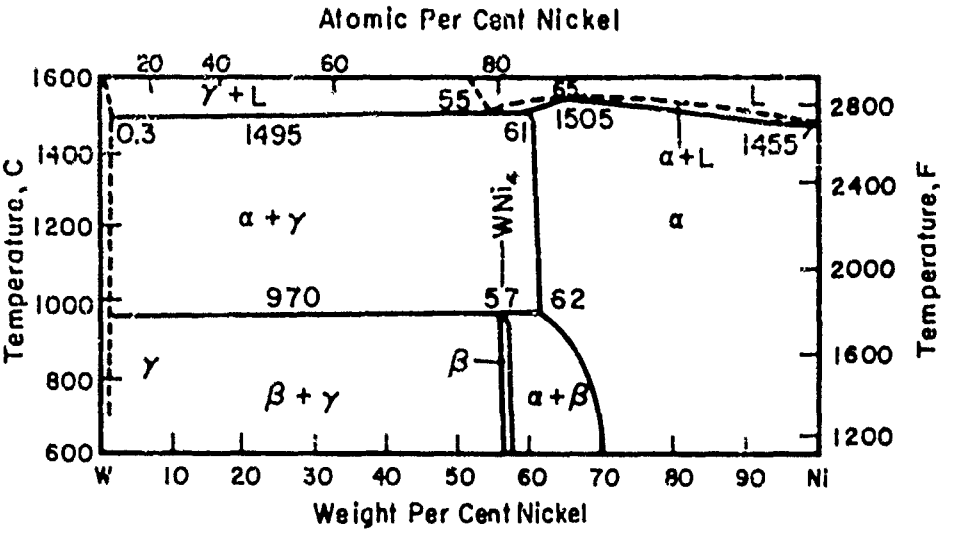
$WCo_3(\gamma)$ is hexagonal of the Ni_3Sn (DO_{19}) type with a = 5.13 A, c = 4.13 A, and c/a = 0.805.[167] $W_6Co_7(\delta)$ is rhombohedral-hexagonal and isotypic with W_6Fe_7 (D8$_5$ type).[167] Its lattice parameters are: a = 4.732 A, c = 25.53 A at the cobalt-rich limit, and a = 4.761, c = 25.72 A at the tungsten-rich limit.[167]



W_2Hf has the $MgCu_2$-type structure (C15) with a = 7.584 kX.[32] Elliot reports the lattice parameter as a = 7.556 kX.[176] The solubility of tungsten in β-hafnium is approximately 13 weight per cent at 1930 C. It is about 0.9 weight per cent in α-hafnium at 1520 C.[32] Braun and Rudy determined the peritectic temperature as 2540 ± 50 C, the eutectic temperature as 1930 ± 30 C, and the eutectoid temperature as approximately 1730 C.[196] They[196] show an α-tungsten solubility field smaller (6 weight per cent maximum solubility) than that shown by Grant and Gleissen[32].



WFe_3 is dimorphous with the hexagonal Mg_2Zn_3 ($C14$) structure, with $a = 4.735$ kX, $c = 7.700$ kX, $c/a = 1.627$.[172] Sykes reports the δ-phase as W_6Fe_9 with $a = 4.731$ kX, $c = 25.76$ kX, and $c/a = 5.440$. The structure has trigonal Laue symmetry with 39 to 40 atoms per unit cell.[173] Arnfelt reported the δ-phase as W_6Fe_7 ($D8_5$ type) with 13 atoms per unit cell. The structure is rhombohedral with $a = 9.04$ A and $\alpha = 30° 39.5'$.[174] The solubility of iron in tungsten is 0.8 weight per cent at 1640 C with little change in solubility with temperature.[175]

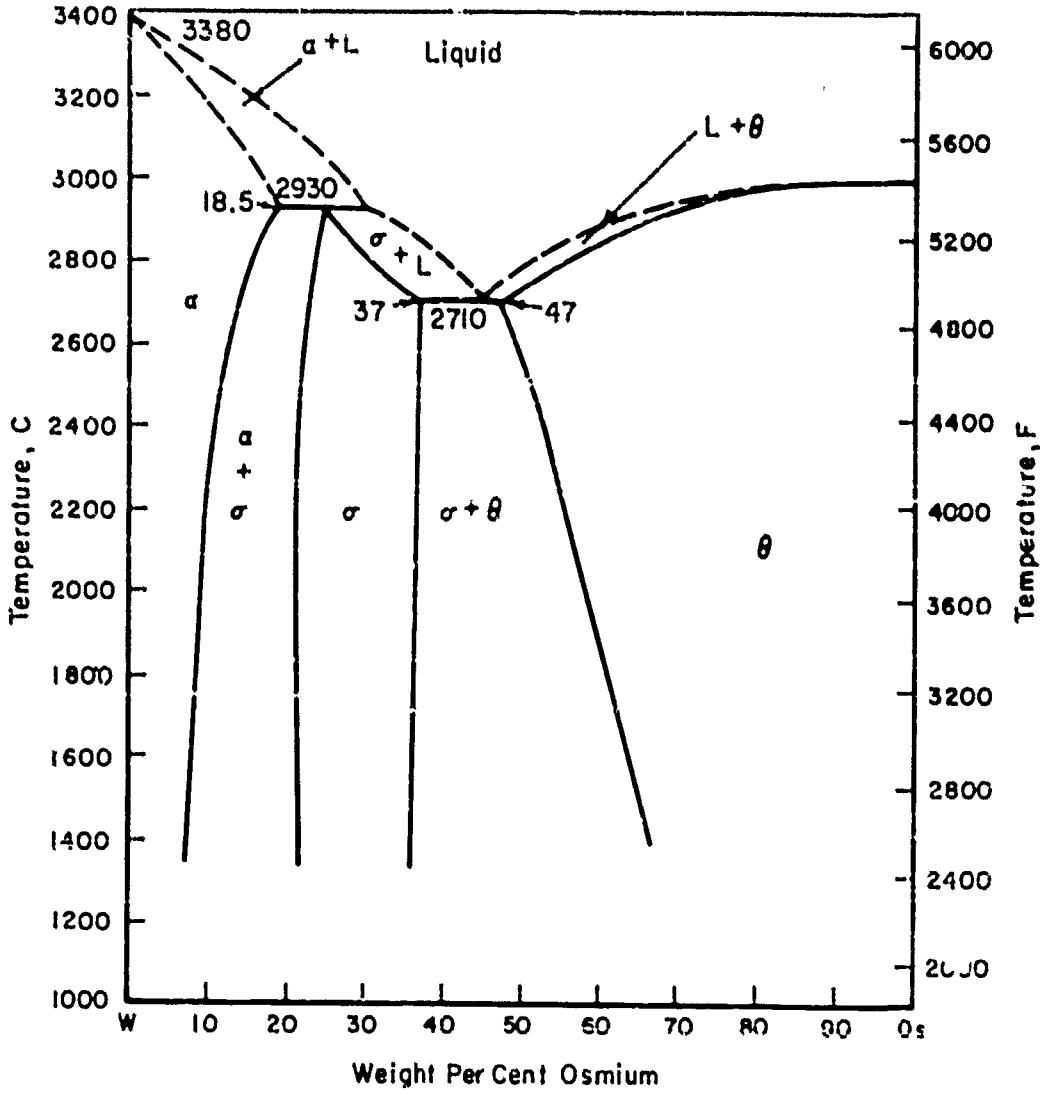


WNi_4 is body-centered tetragonal with a = 5.730 ± 1 A, c = 3.553 ± 1 A, and c/a = 0.620, with 10 atoms per unit cell in ordered positions.[177] The solubility of nickel in tungsten is about 0.3 weight per cent at 1495 C.[178]

SOLUBILITY OF NITROGEN IN TUNGSTEN[197]
(1 Atm Pressure)

Temperature, C	Weight Per Cent Nitrogen	Atomic Per Cent Nitrogen
2400	0.38×10^{-3}	0.50×10^{-2}
2000	0.11×10^{-3}	0.14×10^{-2}
1600	0.19×10^{-4}	0.25×10^{-3}
1200	0.13×10^{-5}	0.17×10^{-4}

A nitride of the approximate composition W_2N has a face-centered cubic lattice of tungsten atoms with interstitial nitrogen atoms, a = 4.126 A.[193] Schönberg observed a hexagonal phase of the approximate composition WN. This phase is isomorphous with WC and has the lattice constants a = 2.893A, c = 2.826 A, and c/a = 0.977.



The σ-phase, W_3Os has the tetragonal β-uranium type of structure with a = 9.62 A, c = 4.93 A, and c/a = 0.518. These lattice parameters were measured at a composition of 33.3 atomic per cent (34 weight per cent) osmium. The solubility of osmium in tungsten is approximately 18.5 weight per cent at 2930 C, decreasing to 9.5 weight per cent at 2200 C. The solubility of tungsten in osmium is 53 weight per cent at 2710 C, decreasing to 35 weight per cent at 1500 C.[78]

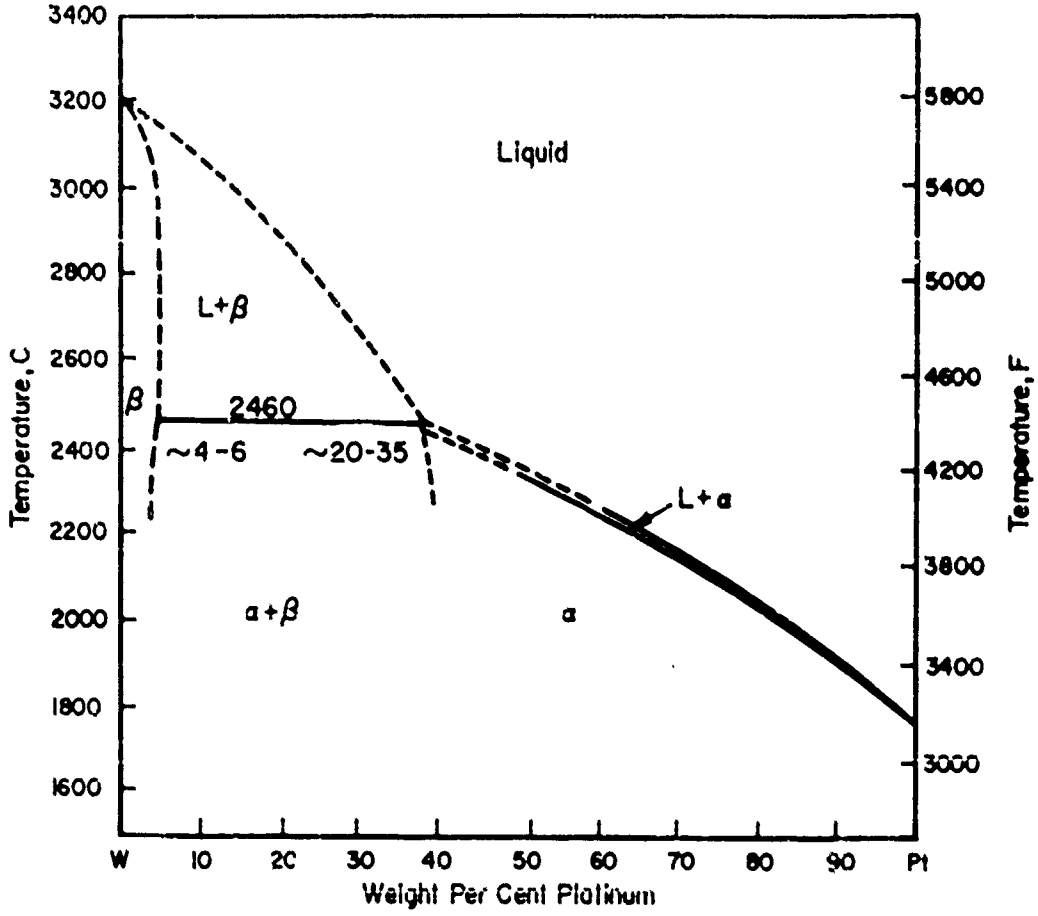
OXIDES OF TUNGSTEN

WO_2 has a very narrow range of homogeneity. The structure is monoclinic, isomorphous with MoO_2 with a = 5.560 A, b = 4.884 A, c = 5.546 A, β = 118.93°, and 12 atoms per unit cell.[199]

A one-phase region exists between the composition $WO_{2.65}$ and $WO_{2.75}$. The structure is monoclinic with the lattice parameters a = 18.32 A, b = 3.79 A, c = 11.04 A, β = 115°2', and 67 atoms per unit cell ($W_{20}O_{59} = WO_{2.72}$).[200]

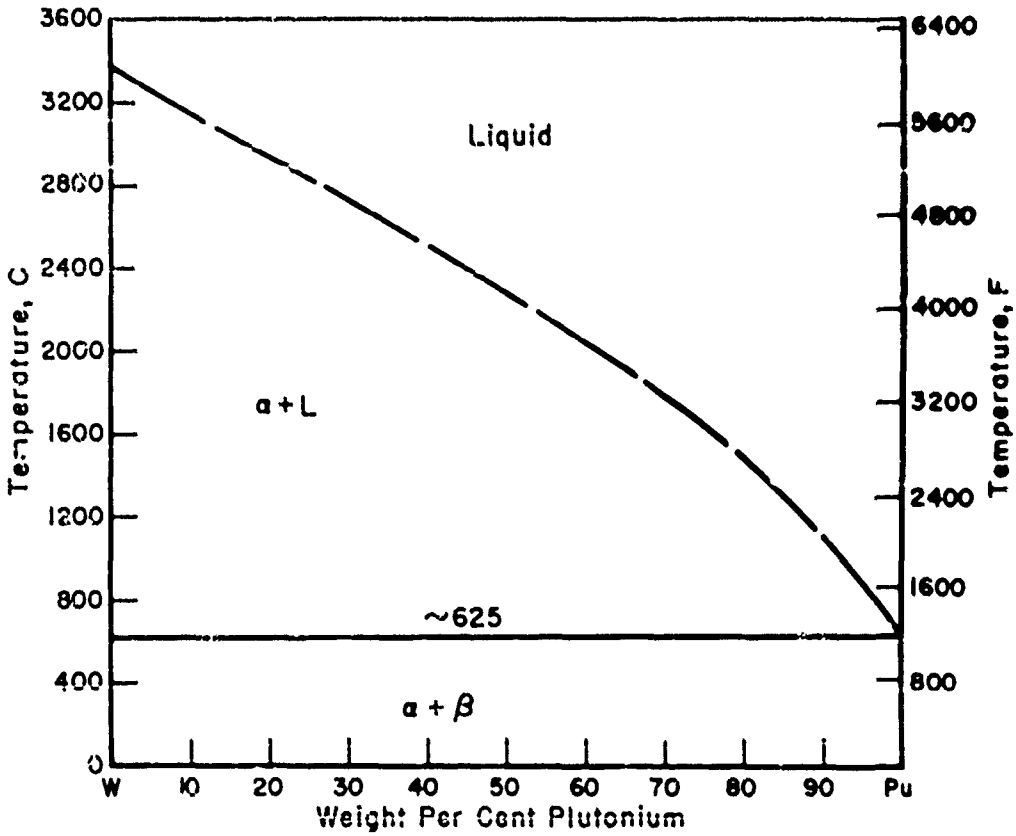
Another one-phase field occurs between the composition $WO_{2.88}$ and $WO_{2.92}$. The structure is monoclinic with the lattice parameters a = 12.1 A, b = 3.78 A, c = 23.4 A, and β = 95° for the composition $WO_{2.90}$ ($=W_{20}O_{58}$). The structure is closely related to that of ReO_3 ($D0_9$ type).[200]

WO_3 is reported to have three structural modifications. The room temperature form is monoclinic with a = 7.285 A, b = 7.517 A, c = 3.835 A, and β = 90.90°.[201] At -50 C, a polymorphic transformation occurs, resulting in a structure of higher symmetry than the room-temperature modification.[202] Between 700 and 750 C, a polymorphic transformation occurs, resulting in a tetragonal structure with a = 5.25 ± 2 A, c = 3.92 ± 2 A, c/a = 0.746, and 8 atoms per unit cell.[203]



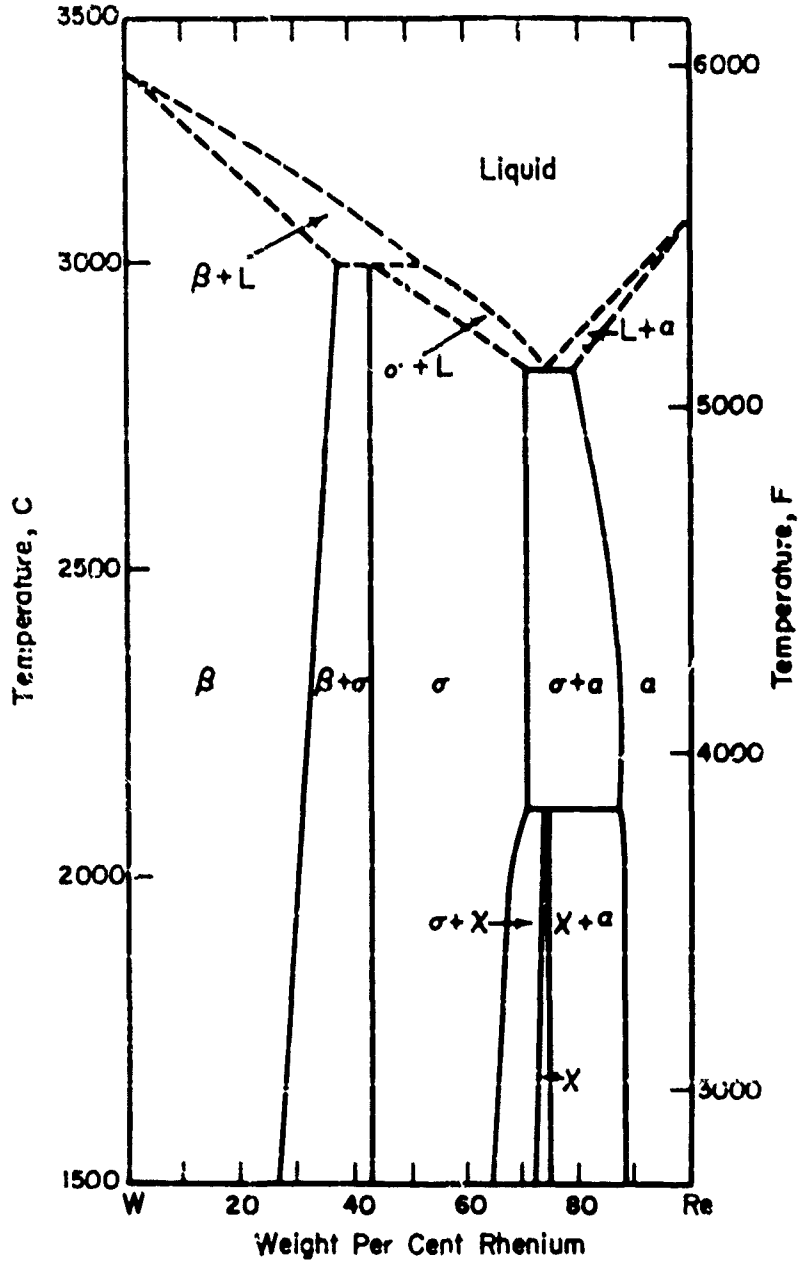
The maximum solubility of platinum in tungsten at the solidus temperature lies between 4 and 6 weight per cent platinum.[178] Platinum and tungsten form a series of solid solutions up to a maximum of 62 weight per cent tungsten.[179] Nemilov found evidence of an order-disorder transformation in the range of 75 atomic per cent tungsten (76 weight per cent).[180]

TUNGSTEN-PLUTONIUM SYSTEM

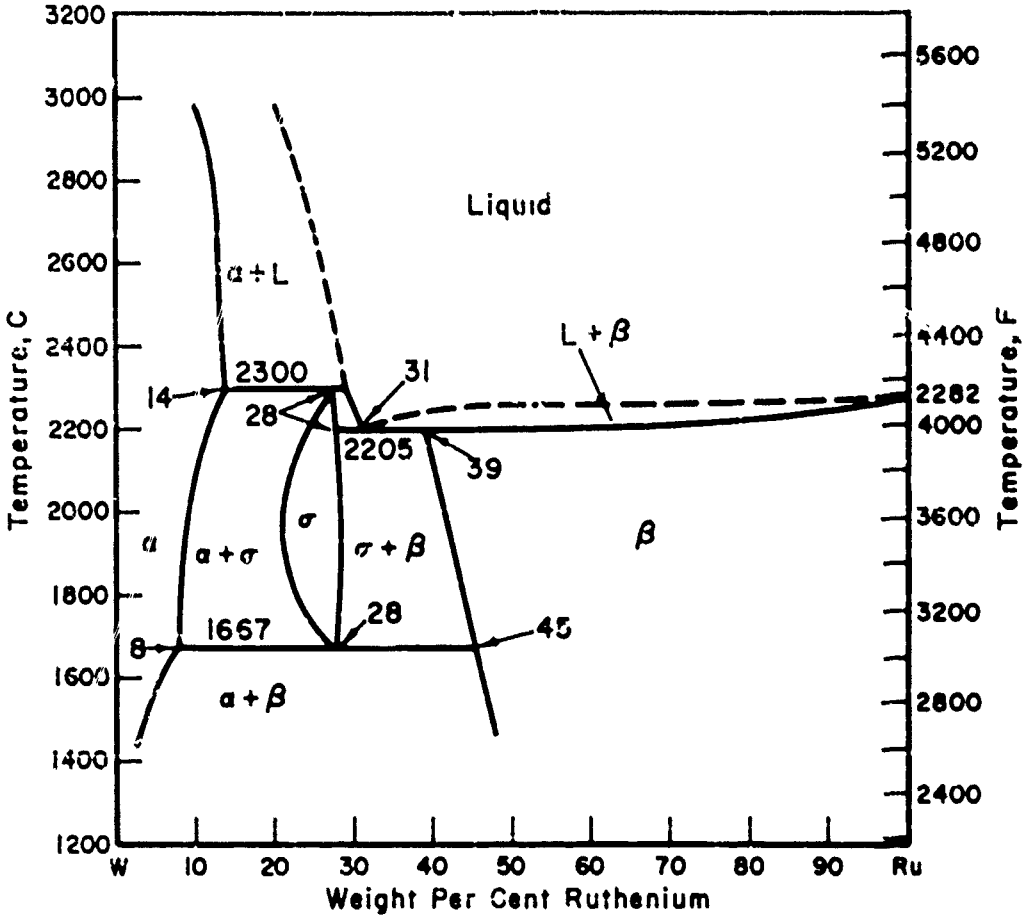


No intermediate phases have been found for this system.[29]

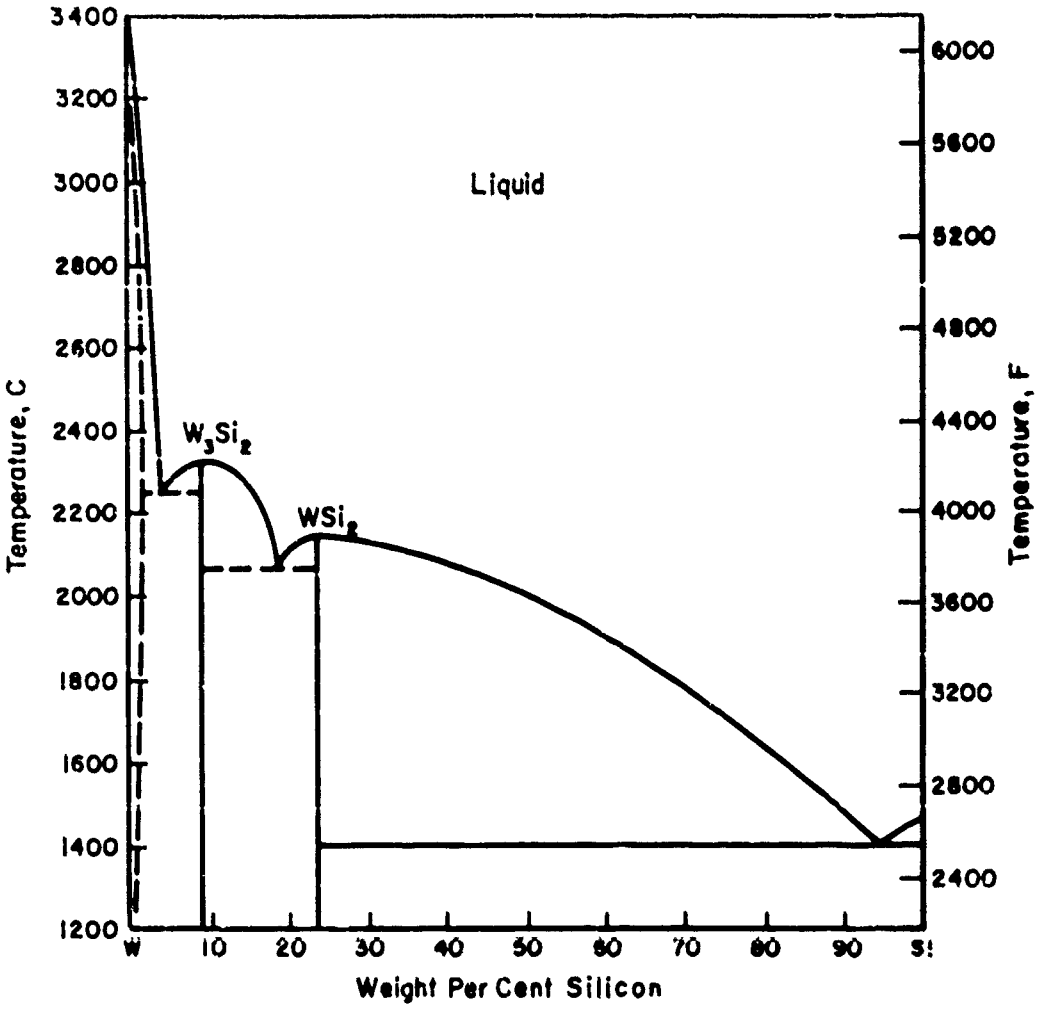
TUNGSTEN-RHENIUM SYSTEM



The α-phase is a tetragonal (D_{2h}^{14}) structure isomorphous with the σ-phase found in iron-chromium alloys.(181) Knapton reported the lattice parameters as a = 9.645 A and c = 5.038 A at 60 weight per cent rhenium.(182) The χ-phase is isomorphous with α-manganese with an approximate composition of Re_3W.(181) The solubility of rhenium in tungsten ranges from 28 weight per cent at 1600 C to 37 weight per cent at 3000 C. The terminal solubility of tungsten in rhenium ranges from approximately 11 weight per cent at 1600 C to 20 weight per cent at 2800 C.(181)

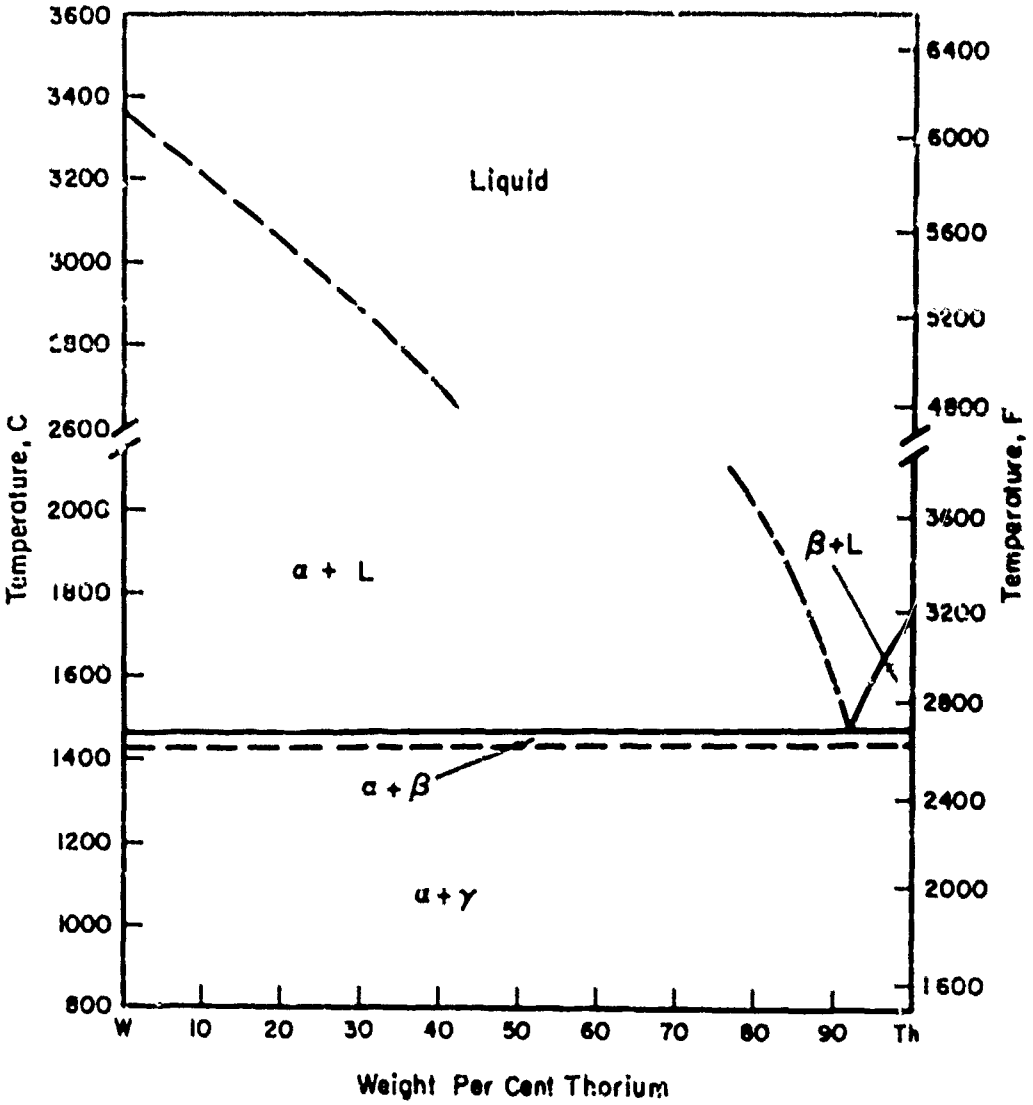


The σ-phase has the stoichiometric composition W_3Ru_2.[147, 183] The lattice parameters are a = 9.55 A and c/a = 0.52.[183] Ruthenium is soluble in tungsten up to 10 atomic per cent (6 weight per cent) ruthenium at 1600 C, increasing to about 23 atomic per cent (14 weight per cent) at 2300 C.[147] The solubility of tungsten in ruthenium is approximately 41 atomic per cent (56 weight per cent) tungsten at 1600 C, increasing to 45 atomic per cent (61 weight per cent at 2205 C).[147]

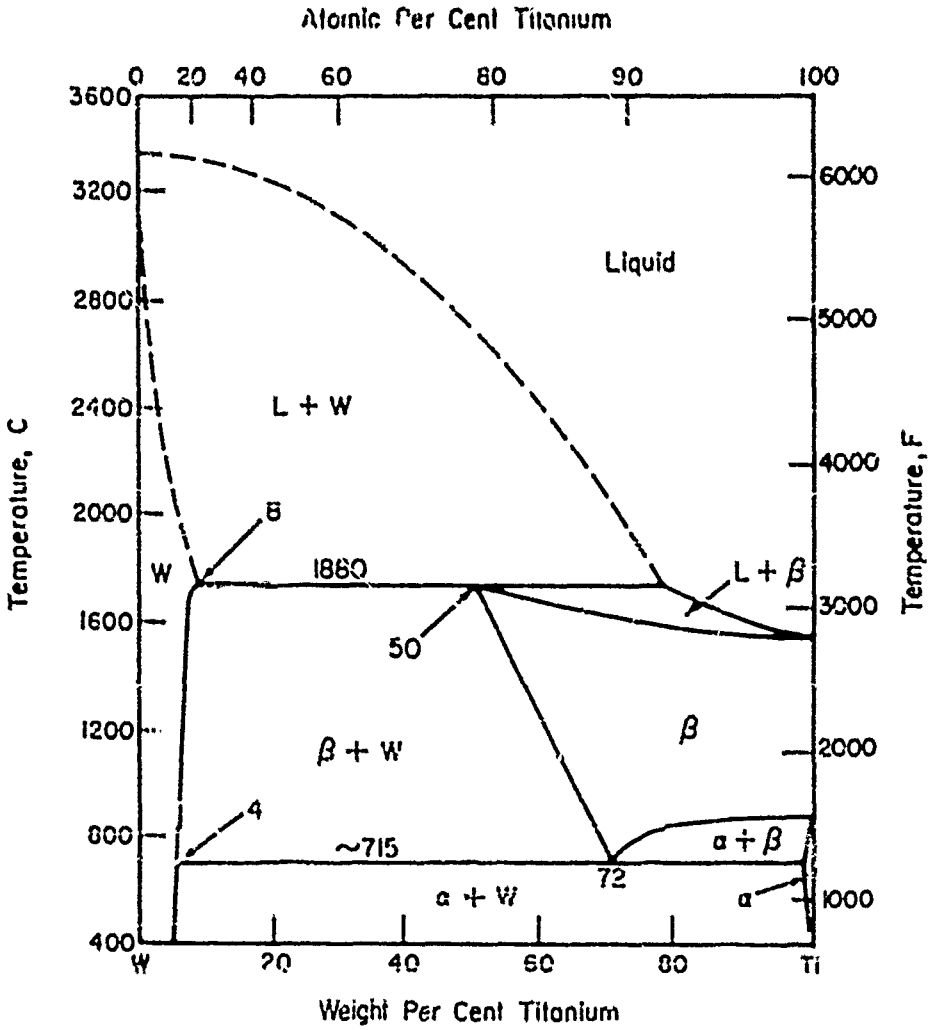


W_3Si_2 (or possibly W_5Si_3) has a tetragonal structure with a = 9.66 A, c = 4.94 A, c/a = 0.52, and four formula units "W_5Si_3" per unit cell.(184) WSi_2 has a tetragonal $MoSi_2$ (C11) type of structure with a = 3.21 A, c = 7.83 A, and c/a = 2.44.(185) The solubility of silicon in tungsten is about 0.9 weight per cent at 1800 C.(186)

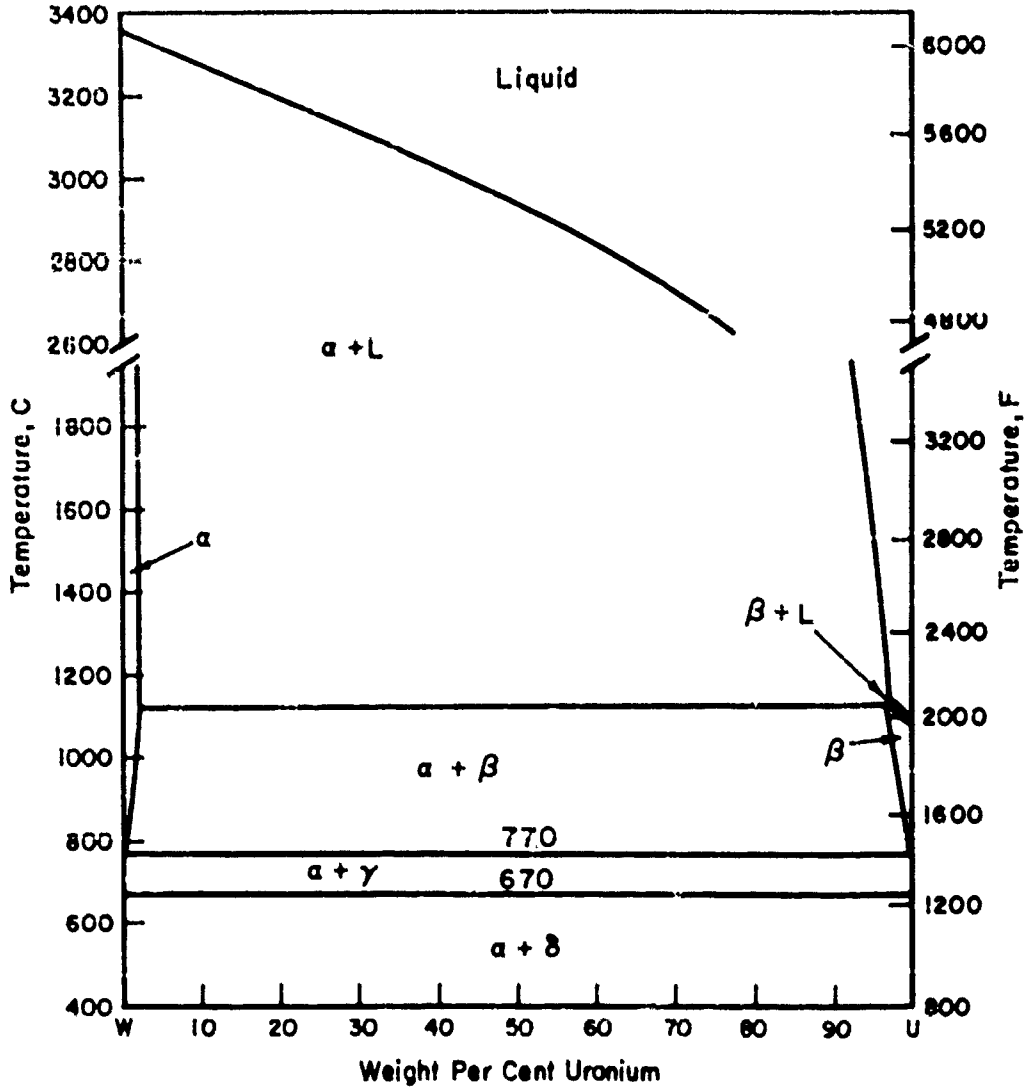
TUNGSTEN-THORIUM SYSTEM



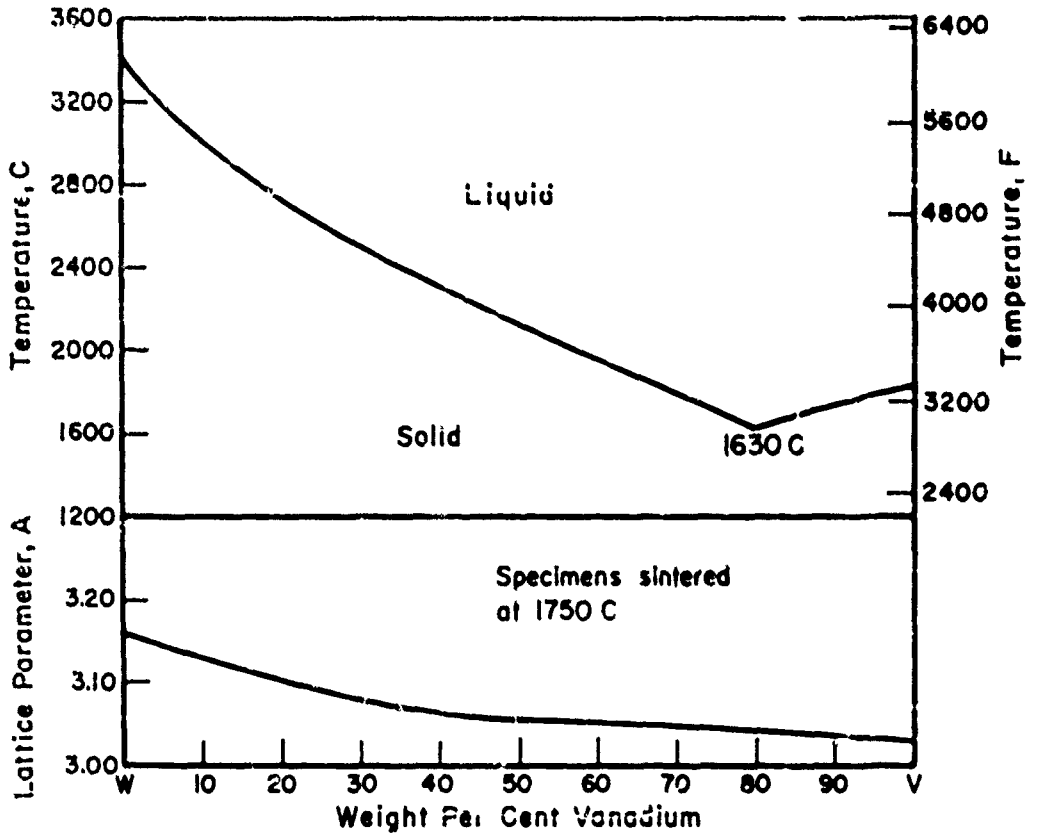
There are no intermetallic compounds in the system. The eutectic temperature is 1475 C. Very little solubility occurs in any of the terminal phases. (187, 188)



The solubility of titanium in tungsten is approximately 8 weight per cent at 1880 C, decreasing to 4 weight per cent at 715 C.[188] The solubility of tungsten in titanium is approximately 0.8 weight per cent at 715 C.[189]

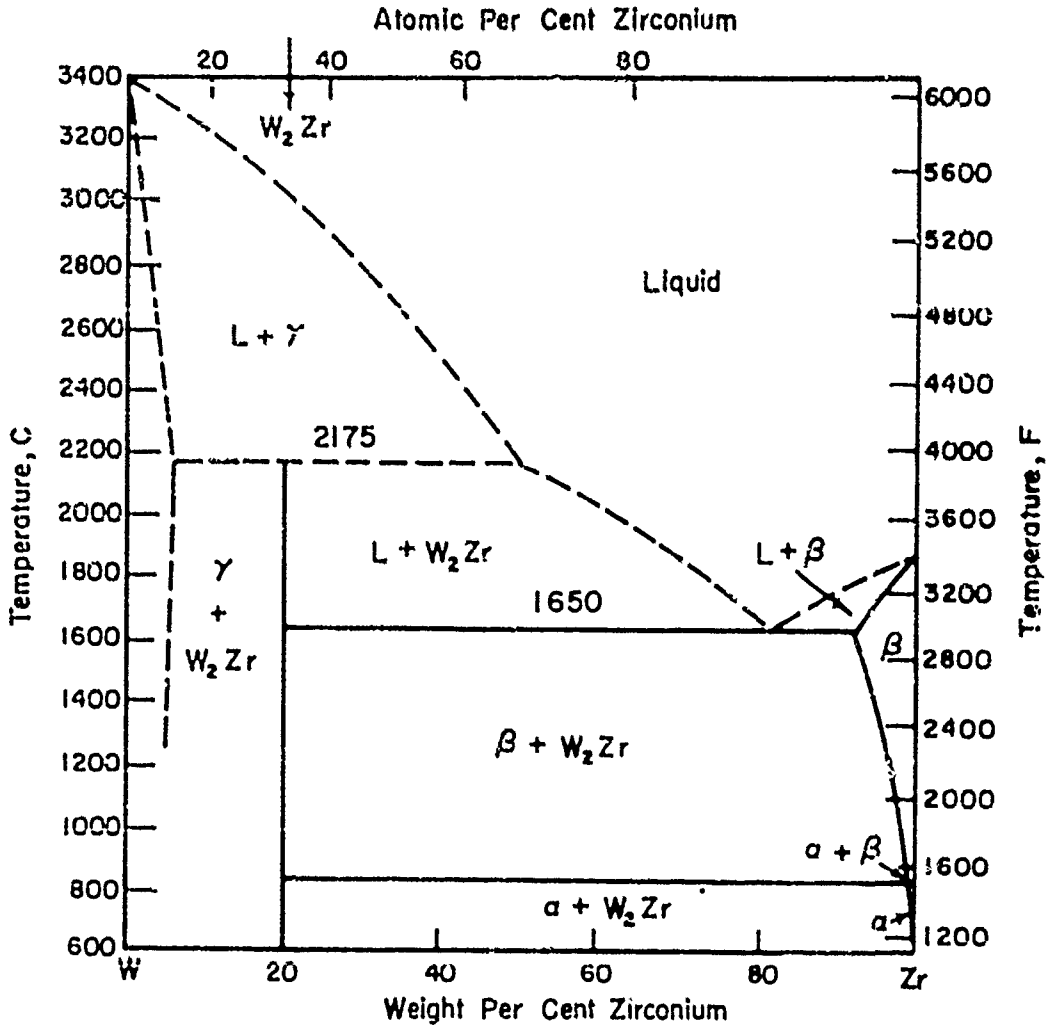


The solubility of uranium in tungsten is about 0.1 atomic per cent at 1000 C.[190] The solubility of tungsten in uranium is 0.2 to 0.7 atomic per cent tungsten.[191] There are no intermetallic compounds in the system.



Lattice-parameter measurements indicate a continuous series of solid solutions at 1750 C.[192] The system is similar to the Mo-Cr system in that a two-phase region possibly exists at lower temperatures.[192, 193]

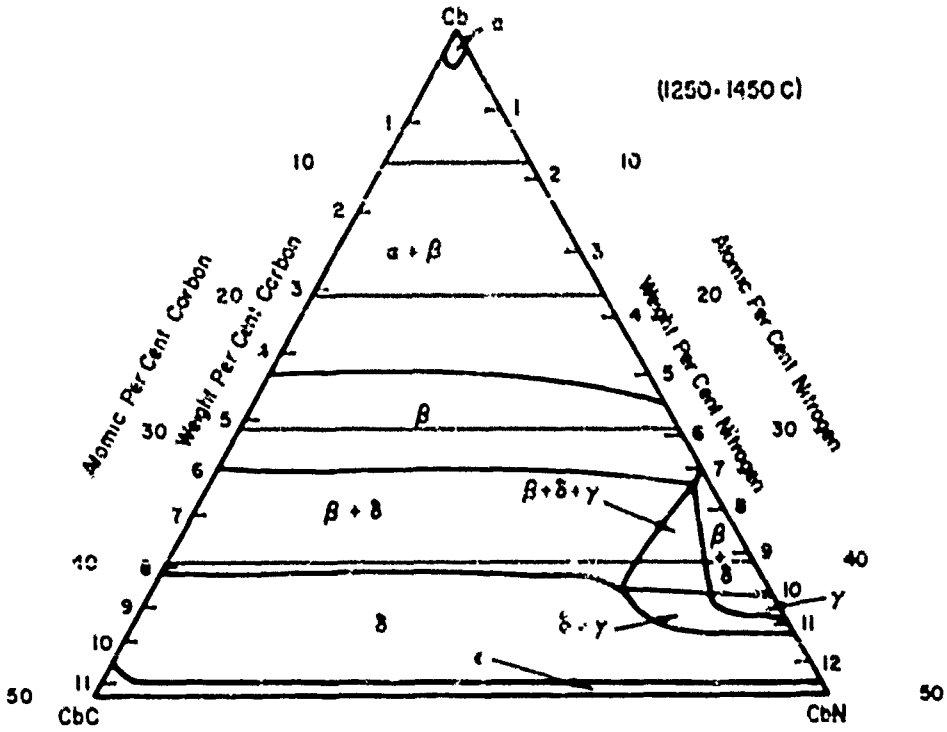
TUNGSTEN-ZIRCONIUM SYSTEM



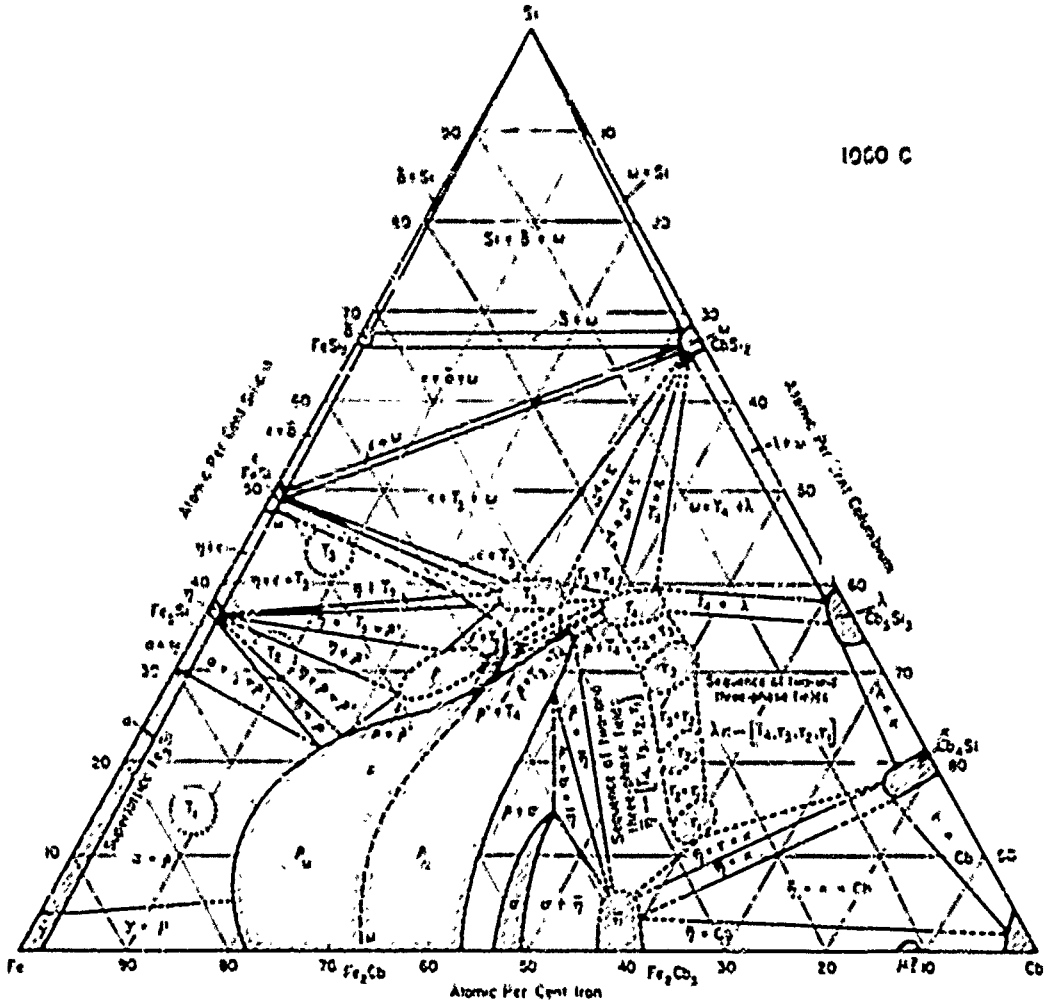
W_2Zr has the cubic $MgCu_2$ (C15) type of structure with a = 7.615 A.[176] The solubility of zirconium in tungsten is about 3 weight per cent at 2160 C.[194] The solubility of tungsten in α-zirconium is less than 0.5 weight per cent tungsten.[195]

TERNARY PHASE DIAGRAMS

COLUMBIUM-COLUMBIUM CARBIDE-COLUMBIUM NITRIDE SYSTEM[204]

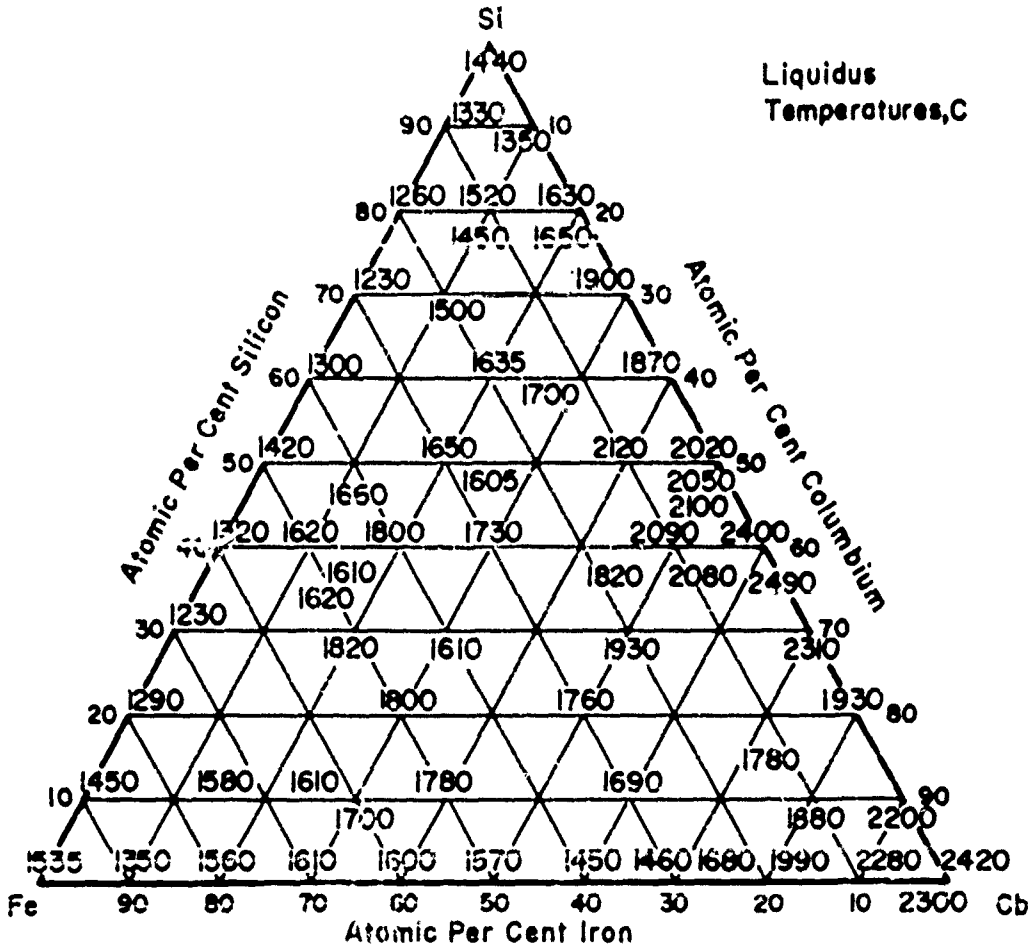


COLUMBIUM-IRON-SILICON SYSTEM(205)



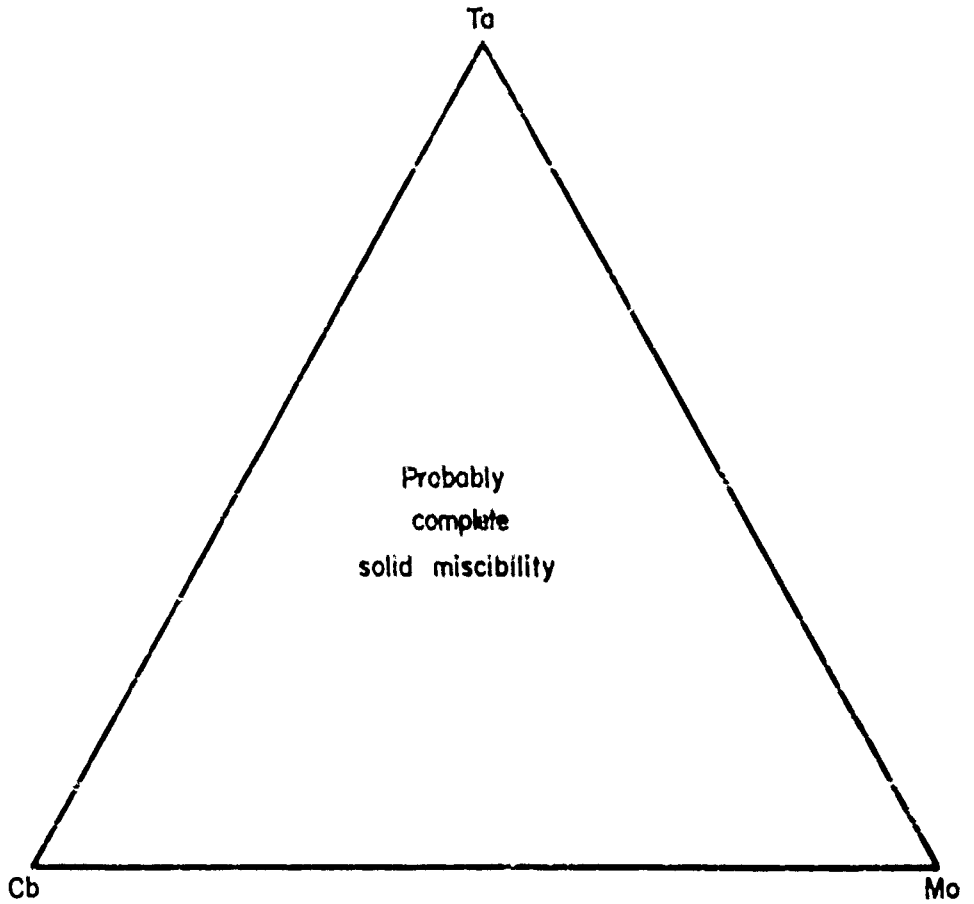
4/61

COLUMBIUM-IRON-SILICON SYSTEM[205]

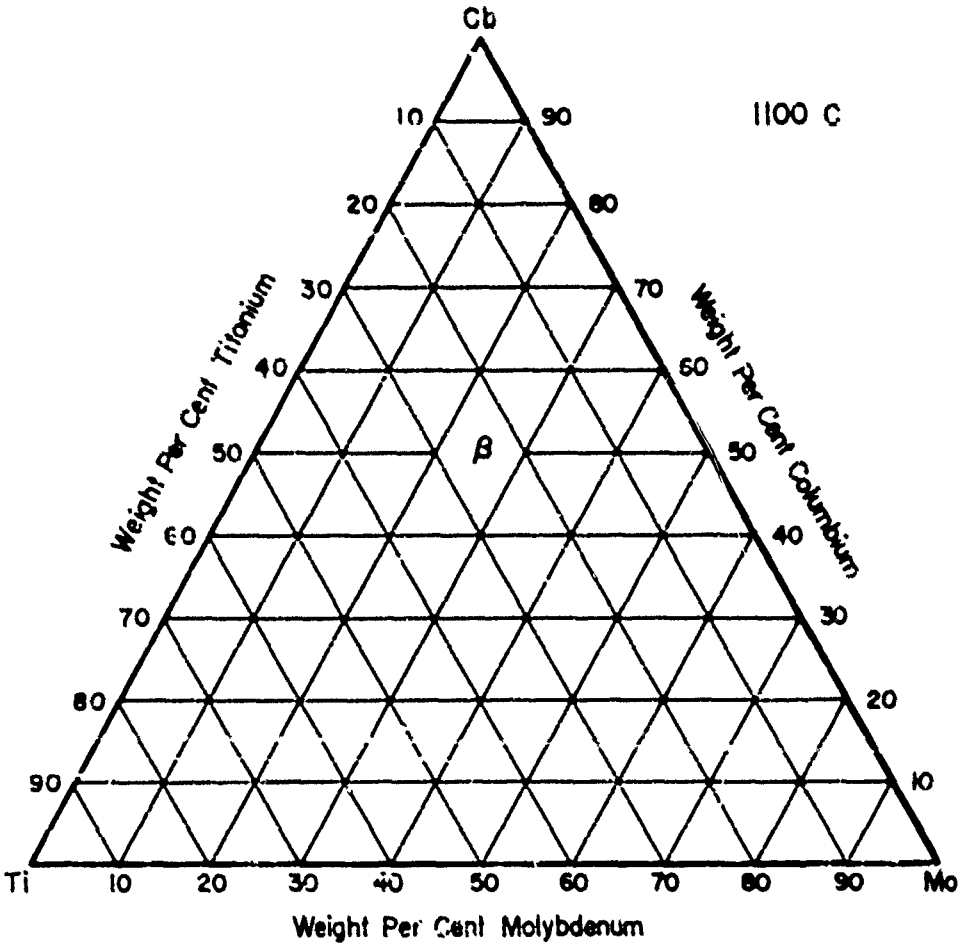


Melting temperatures in the Cb-Fe-Si system (liquidus approximate values only).

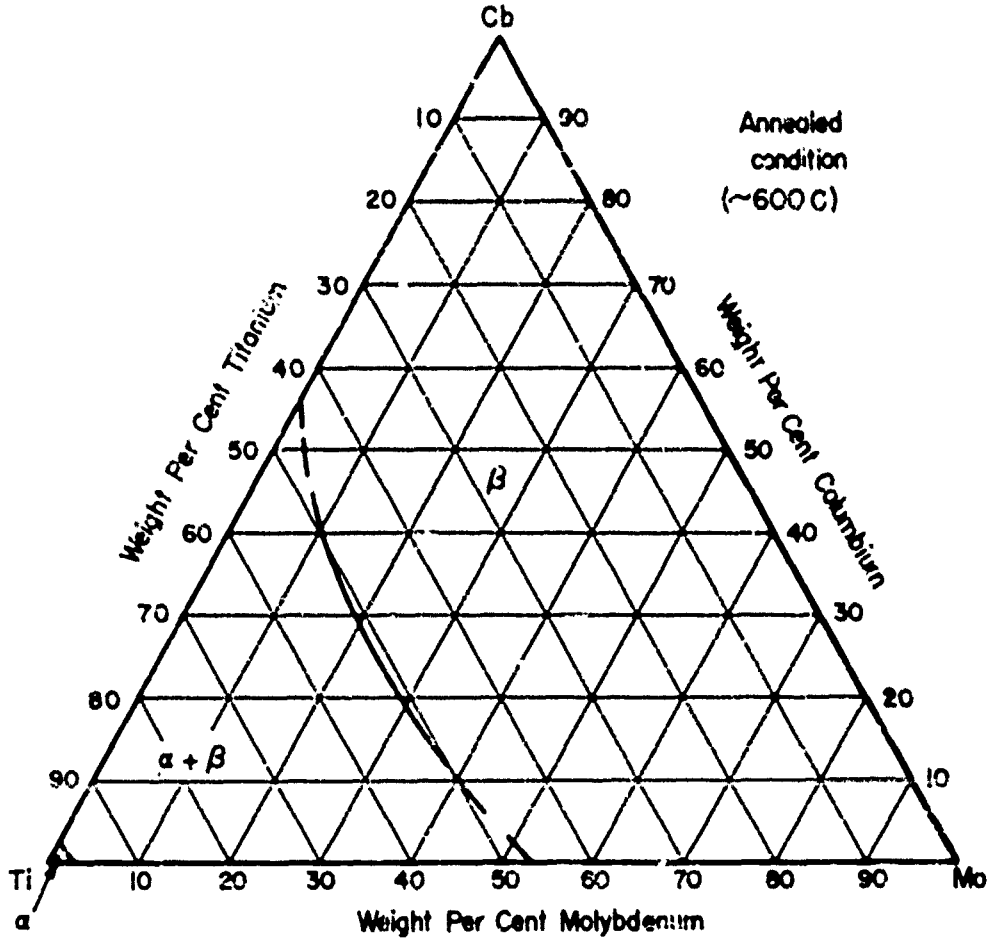
COLUMBIUM-MOLYBDENUM-TANTALUM SYSTEM[206]



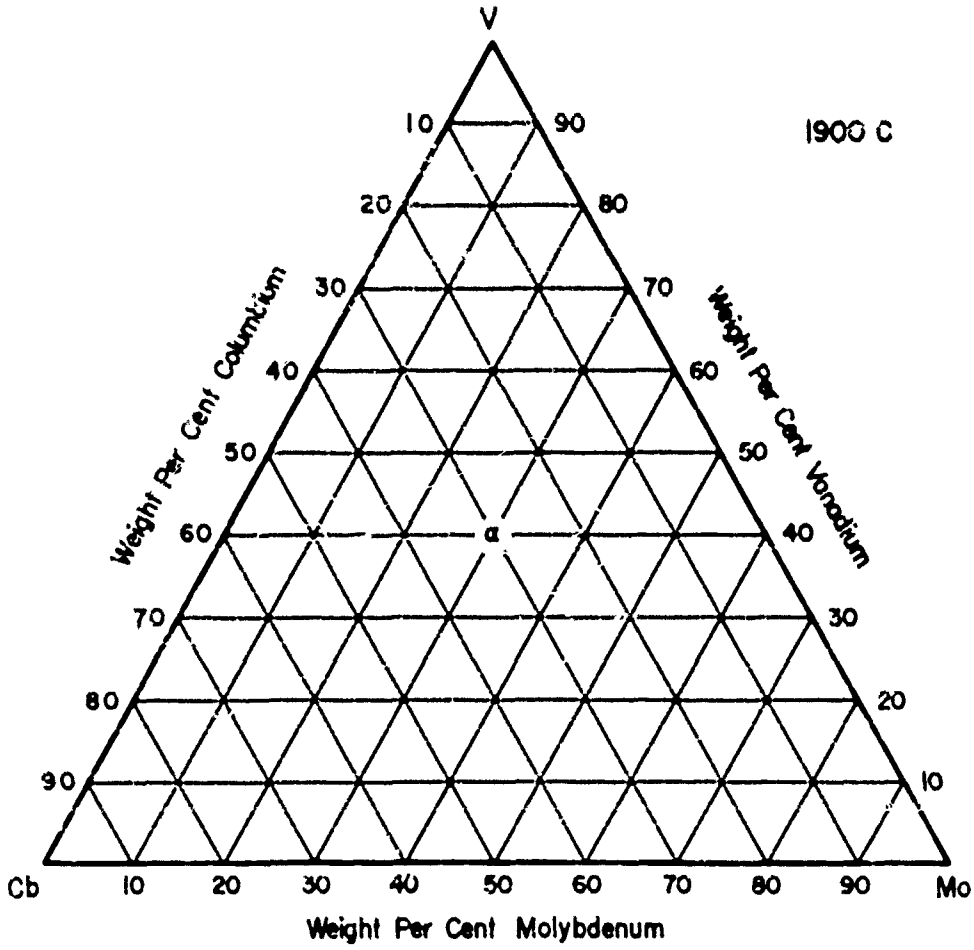
COLUMBIUM-MOLYBDENUM-TITANIUM SYSTEM[207]



COLUMBIUM-MOLYBDENUM-TITANIUM SYSTEM[207]



COLUMBIUM-MOLYBDENUM-VANADIUM SYSTEM[208]



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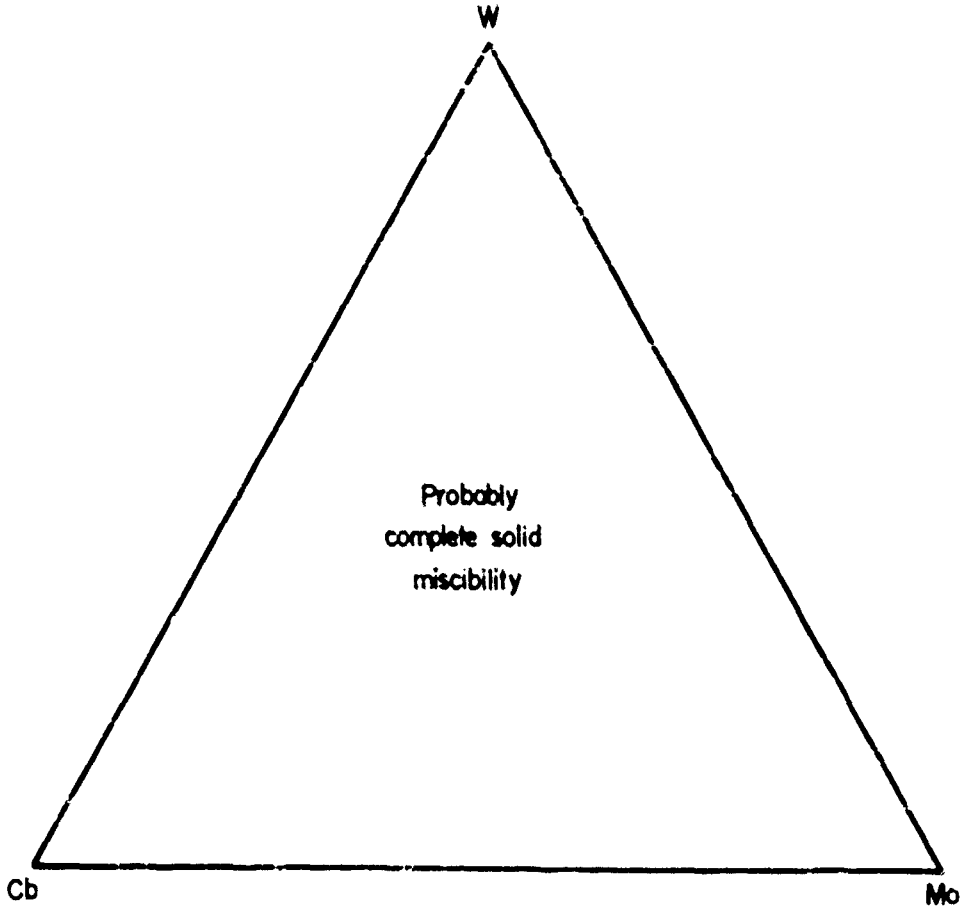
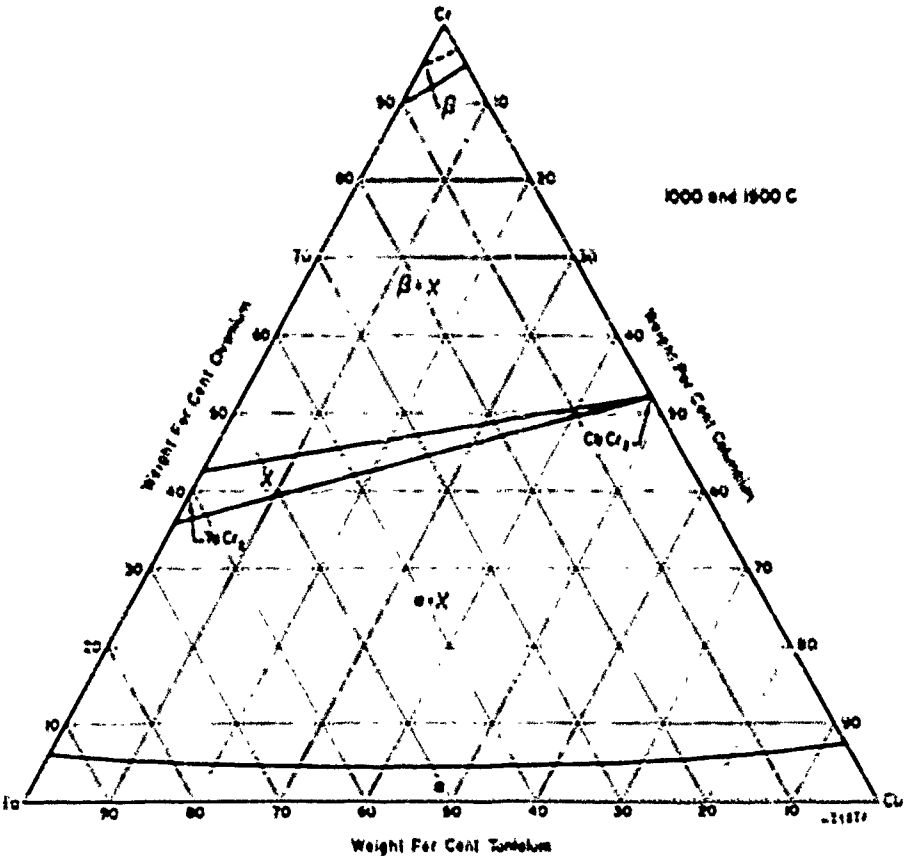
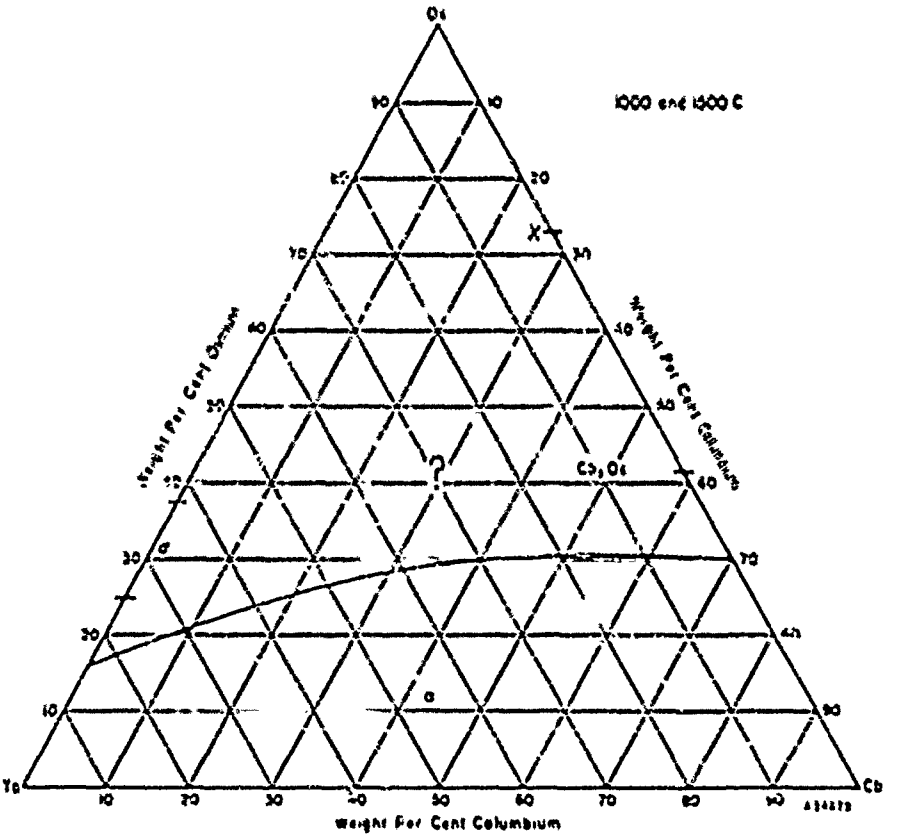
COLUMBIUM-MOLYBDENUM-TUNGSTEN SYSTEM[206]

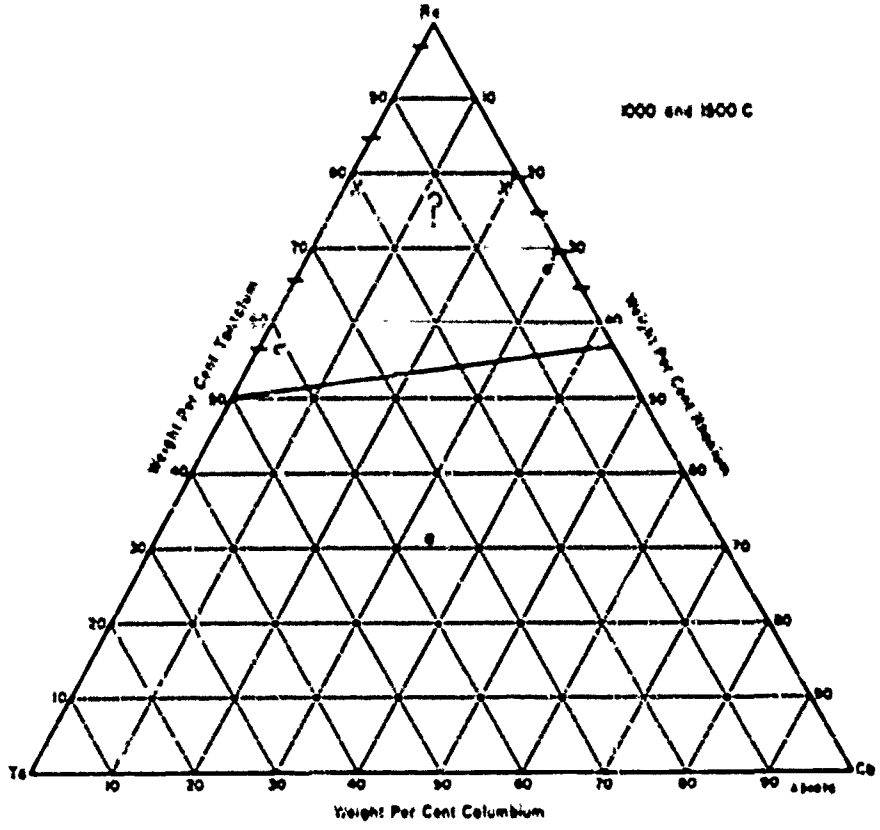



Cr
β
β+X
X
α+X
α
Ta
Cu
1000 and 1900 C
Weight Per Cent Chromium
Weight Per Cent Columbium
Weight Per Cent Tantalum
Ta Cr2
Cb Cr2

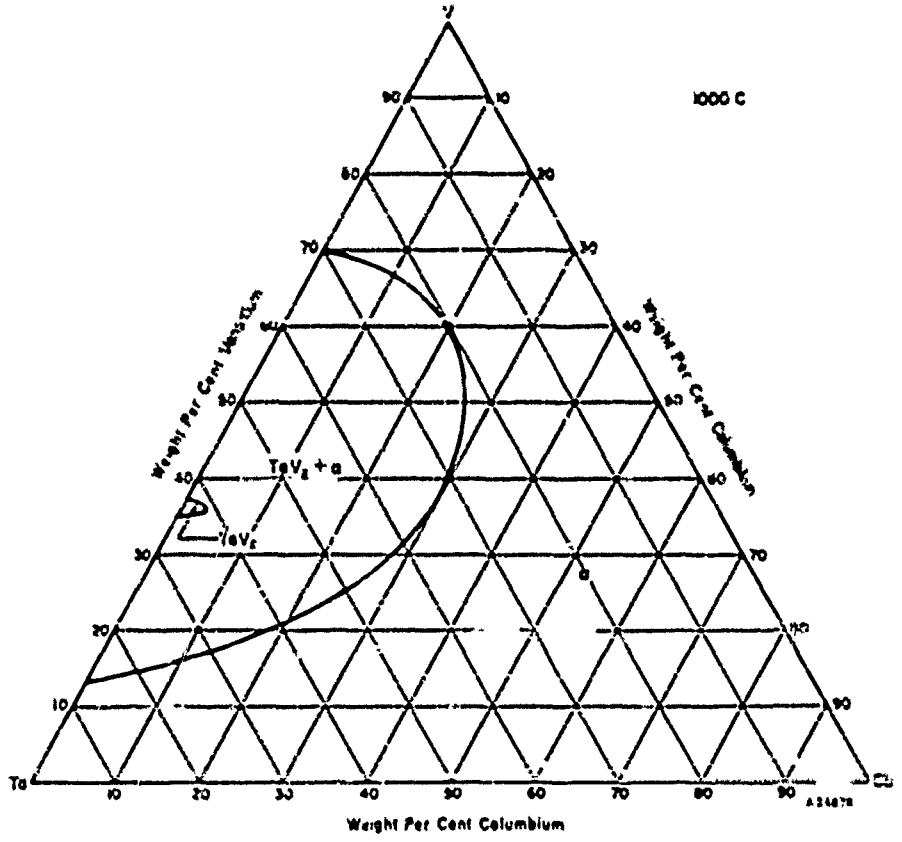
COLUMBIUM-TANTALUM-OSMIUM SYSTEM[406]



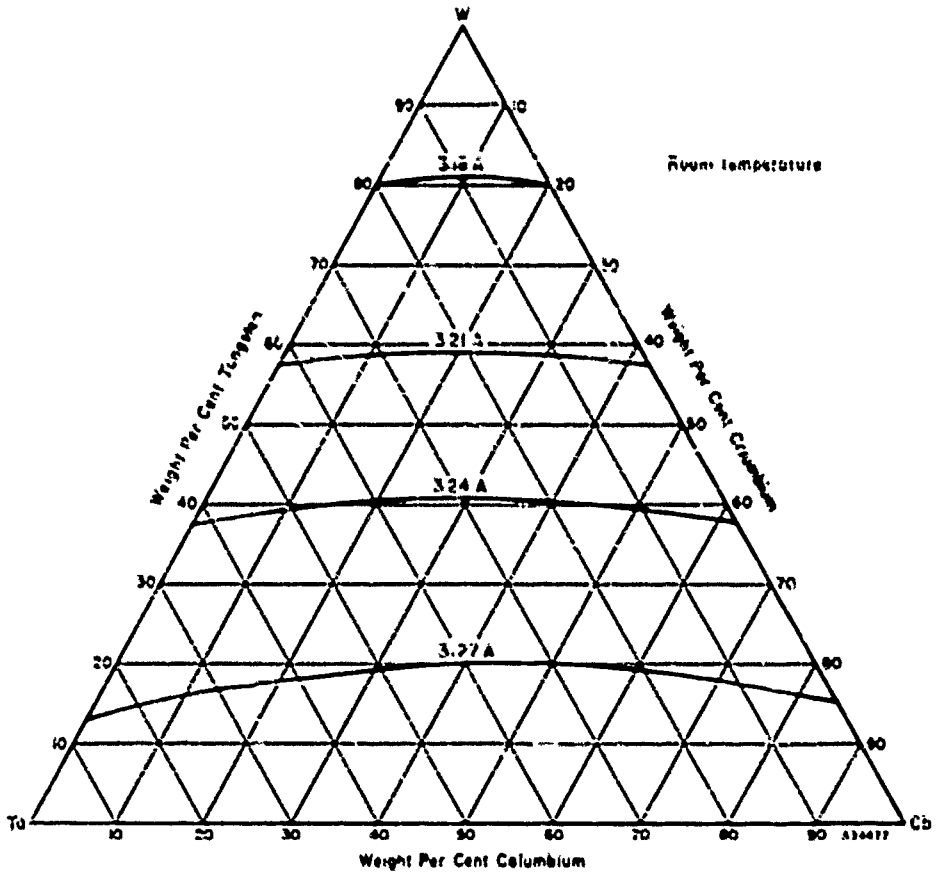
COLUMBIUM-TANTALUM-RHENIUM SYSTEM[206]



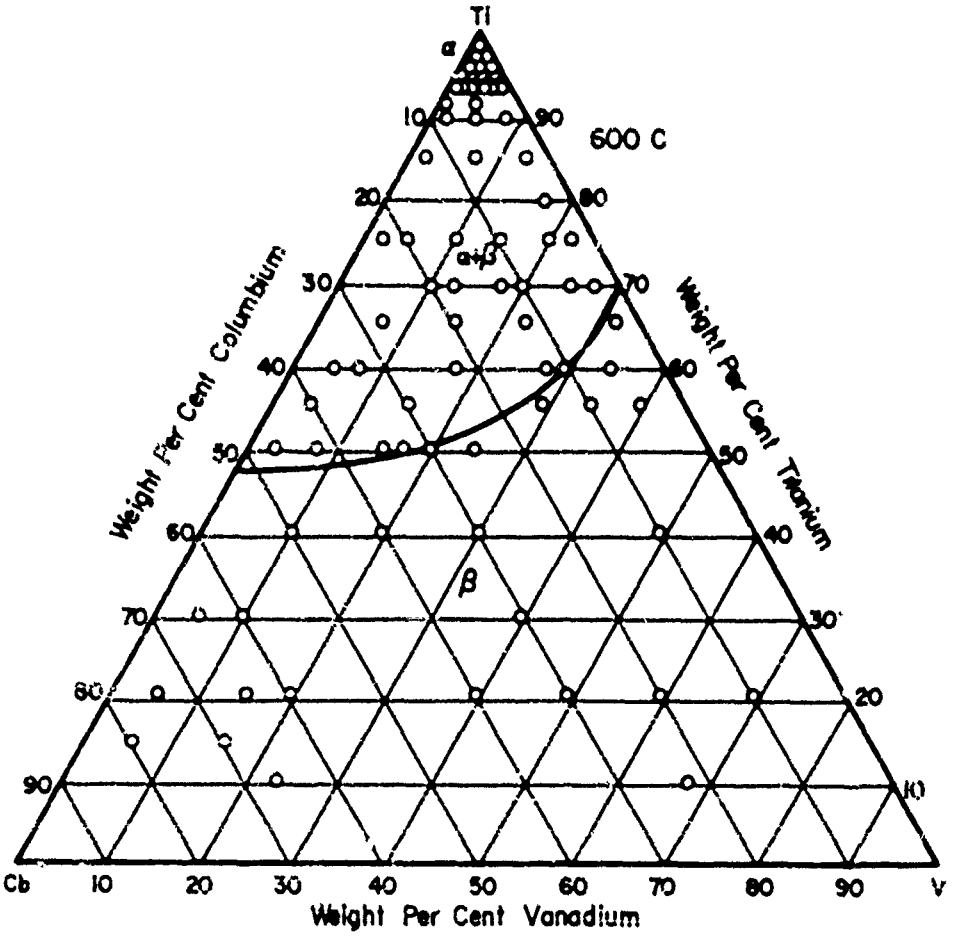
COLUMBIUM-TANTALUM-VANADIUM SYSTEM[206]

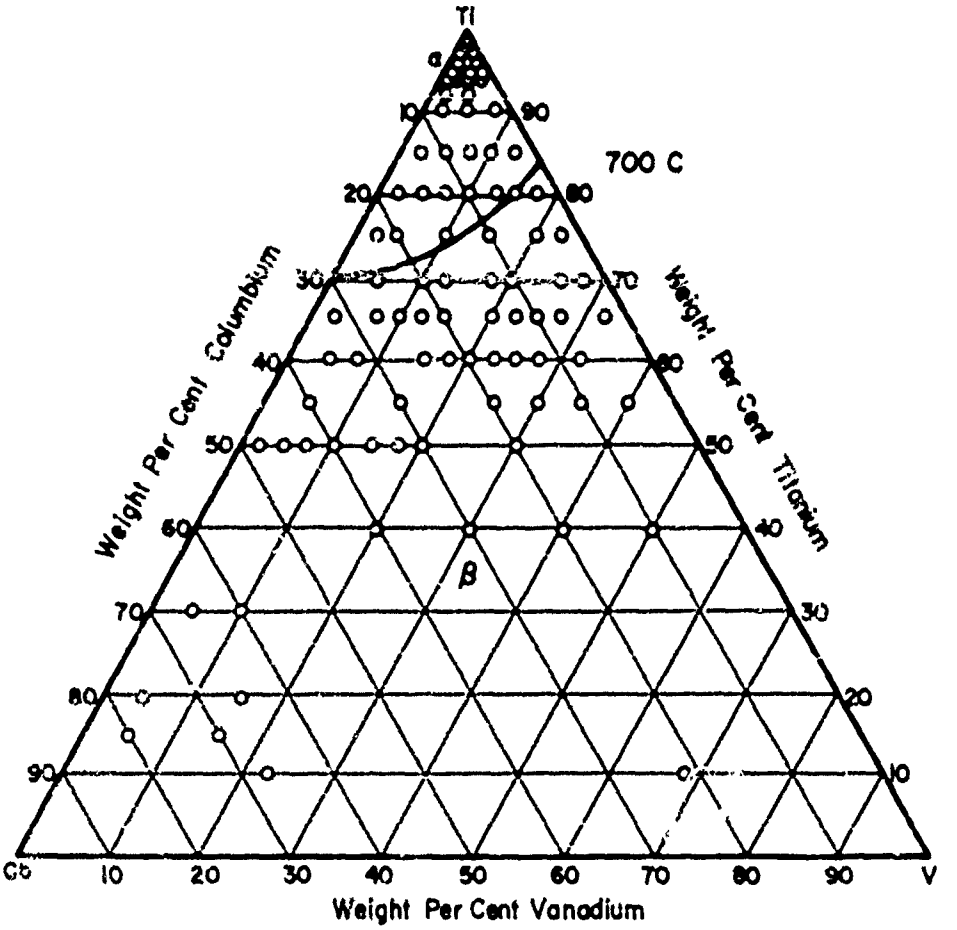


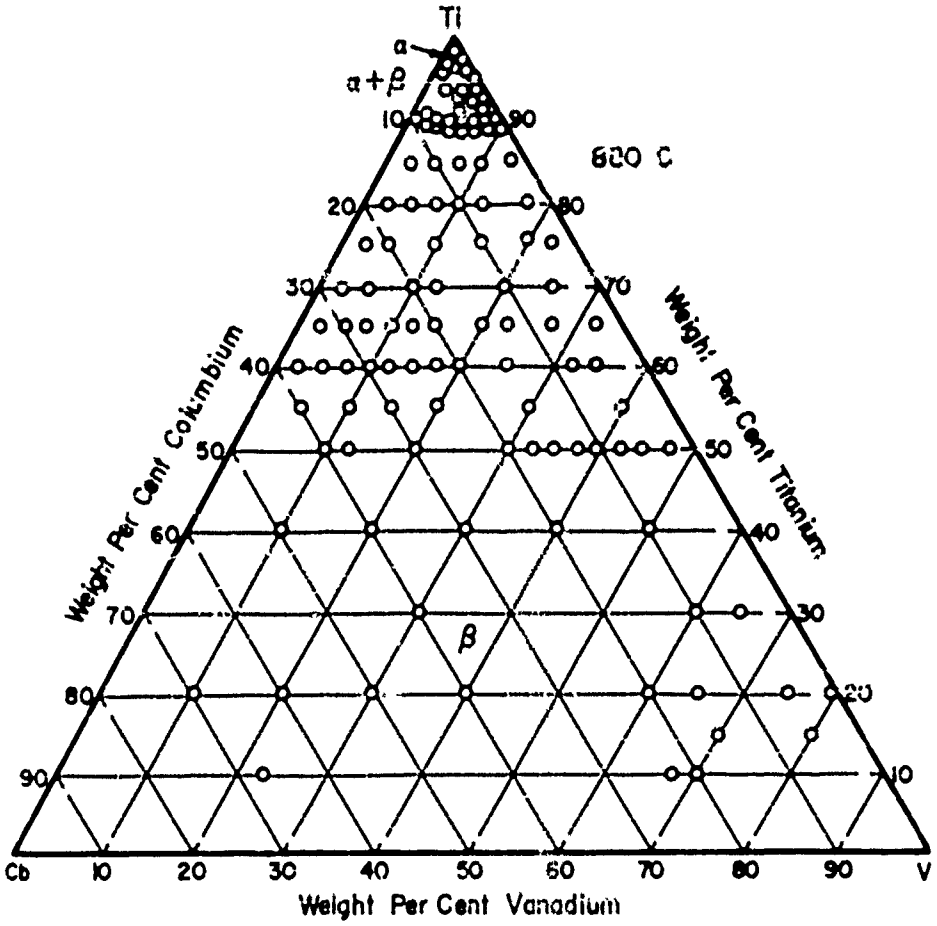
COLUMBIUM-TANTALUM-TUNGSTEN SYSTEM(206)



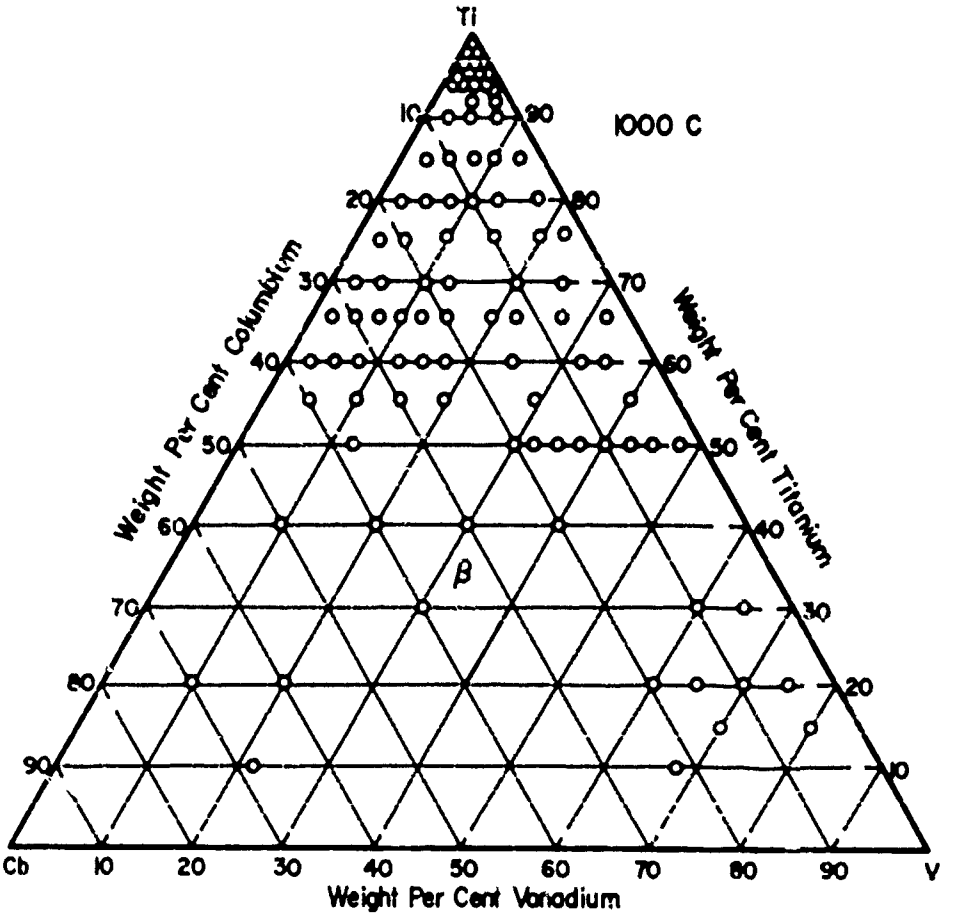
COLUMBIUM-TITANIUM-VANADIUM SYSTEM



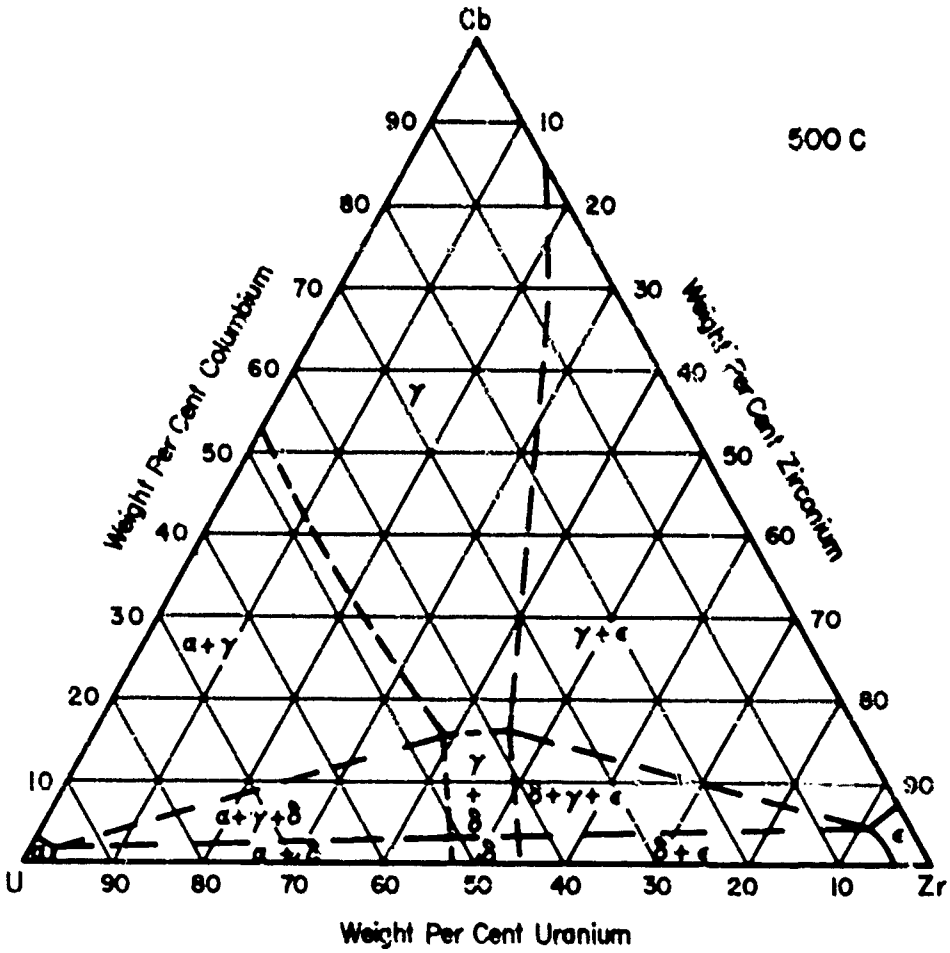

Ti
α
β
700 C
Weight Per Cent Columbium
Weight Per Cent Titanium
Weight Per Cent Vanadium
Cb
V
10
20
30
40
50
60
70
80
90

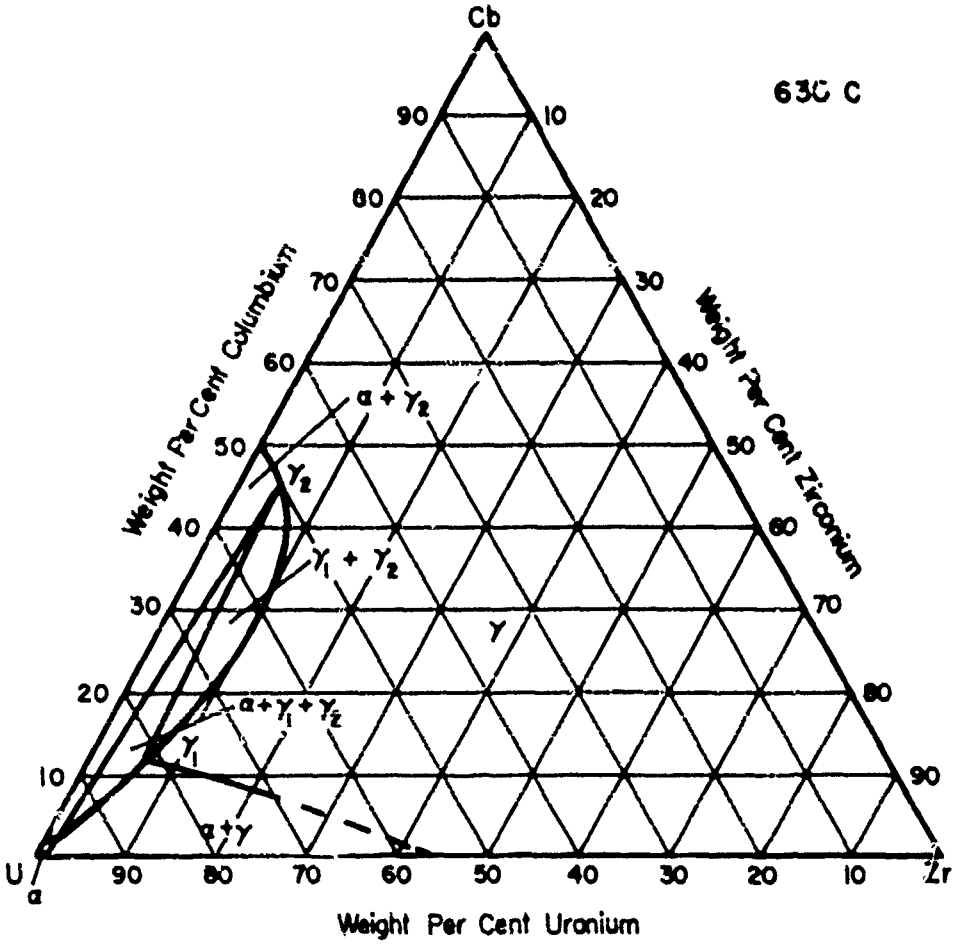

Ti
α
α+β
10
90
620 C
20
80
30
70
40
60
50
50
60
40
70
30
80
20
90
10
β
Cb
10
20
30
40
50
60
70
80
90
V
Weight Per Cent Columbium
Weight Per Cent Titanium
Weight Per Cent Vanadium

COLUMBIUM-TITANIUM-VANADIUM SYSTEM

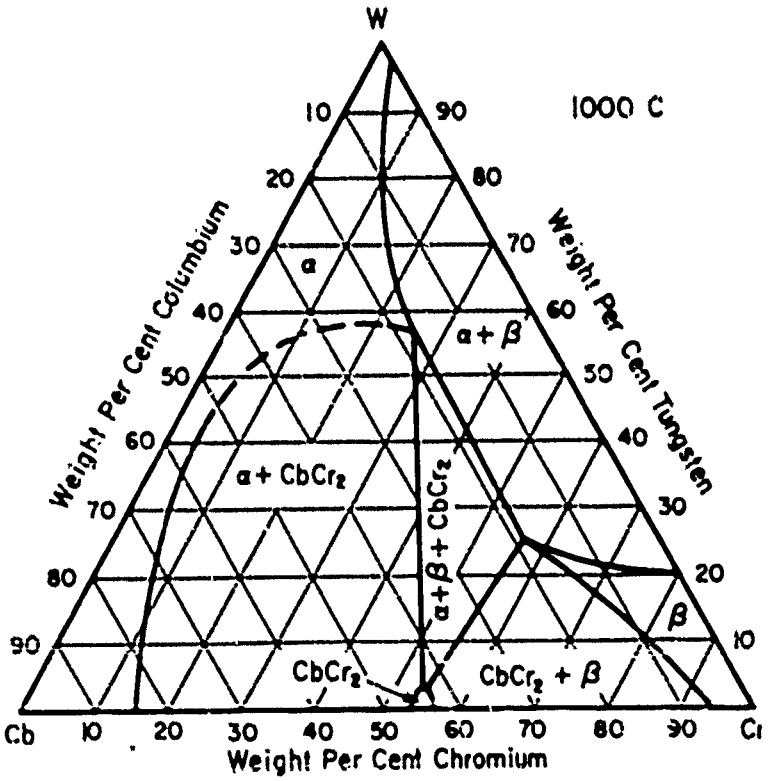


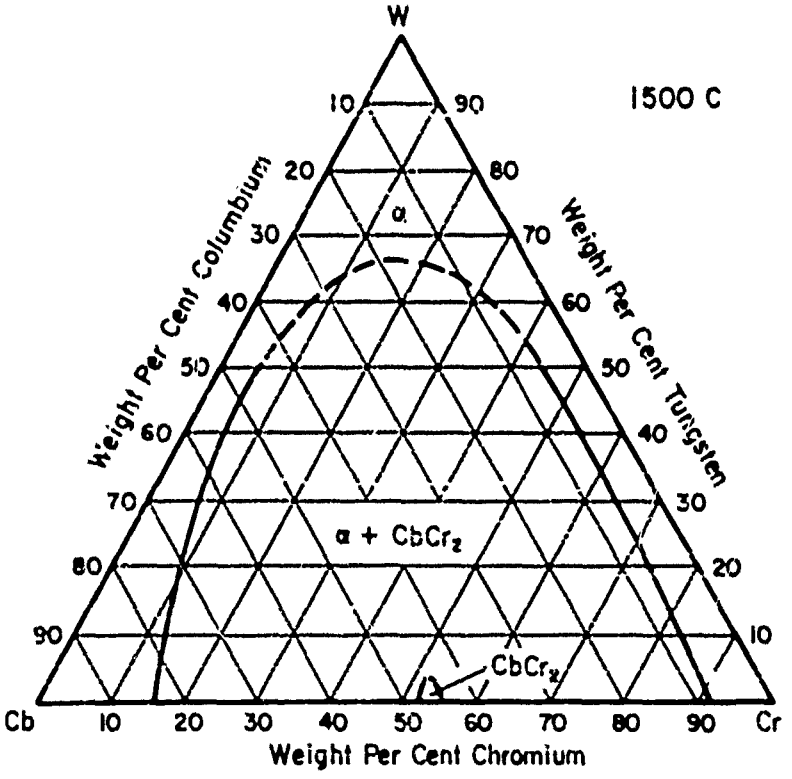
COLUMBIUM-URANIUM-ZIRCONIUM SYSTEM(210)

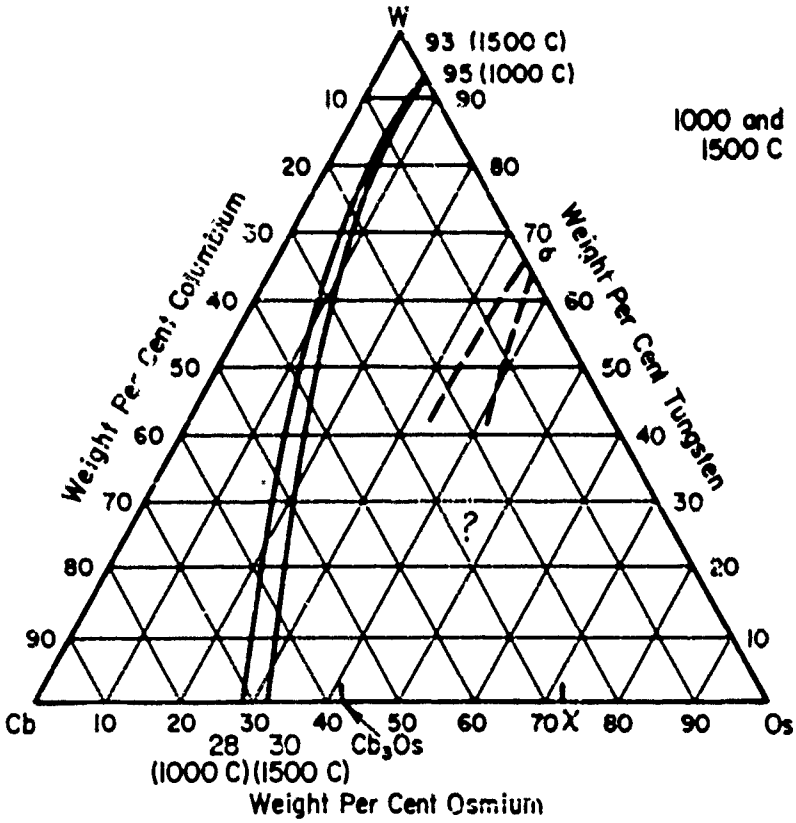



630 C
Cb
Weight Per Cent Columbium
Weight Per Cent Zirconium
Weight Per Cent Uranium
U
Zr
α
α + γ2
γ2
γ1 + γ2
γ
α + γ1 + γ2
γ1
α + γ
90
80
70
60
50
40
30
20
10

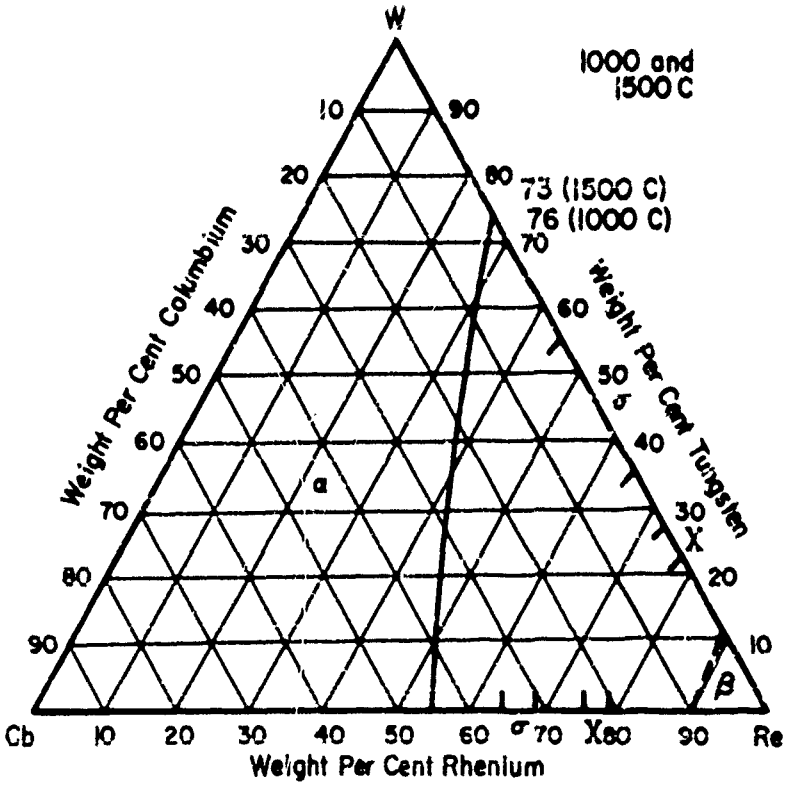
COLUMBIUM-TUNGSTEN-CHROMIUM SYSTEM(206)



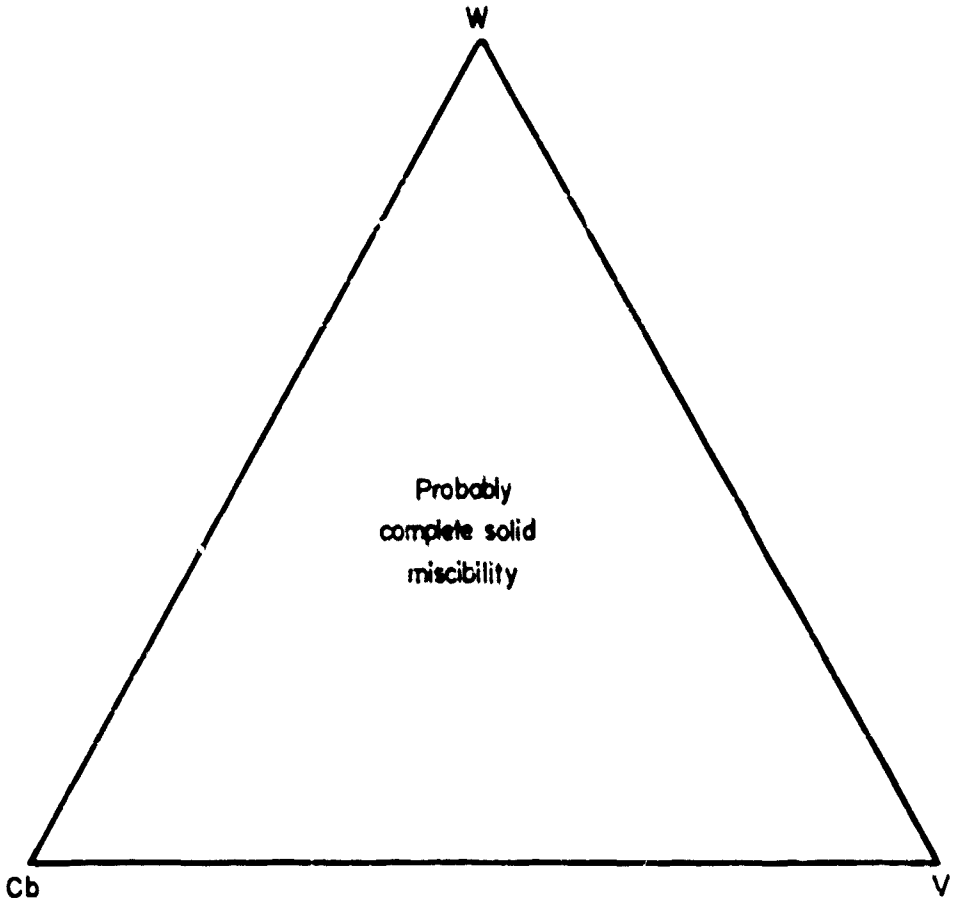

W
1500 C
Weight Per Cent Columbium
Weight Per Cent Tungsten
Weight Per Cent Chromium
Cb
Cr
α
α + CbCr2
CbCr2
10
20
30
40
50
60
70
80
90

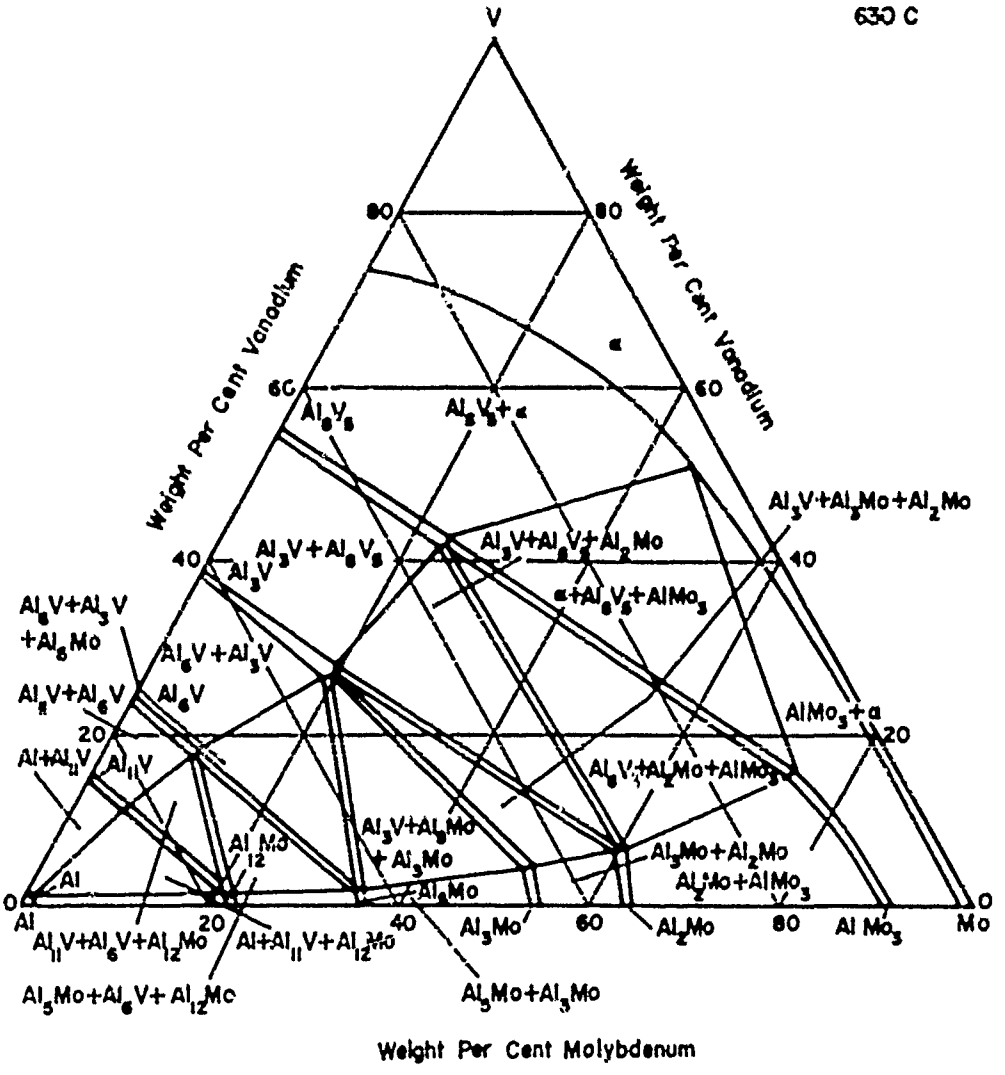

W
93 (1500 C)
95 (1000 C)
1000 and
1500 C
Weight Per Cent Columbium
Weight Per Cent Tungsten
Weight Per Cent Osmium
Cb
Os
?
X
28 30
(1000 C)(1500 C)
Cb_3Os

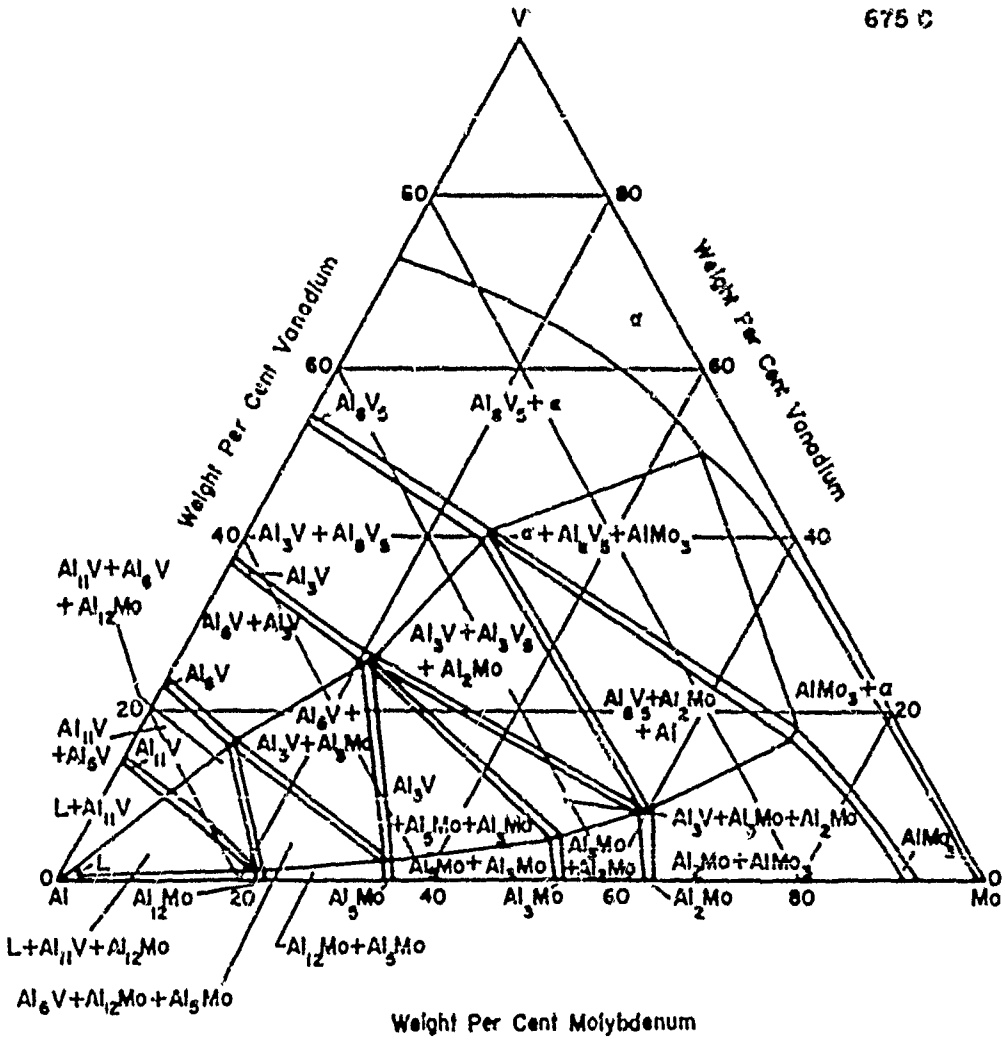
COLUMBIUM-TUNGSTEN-RHENIUM SYSTEM[206]



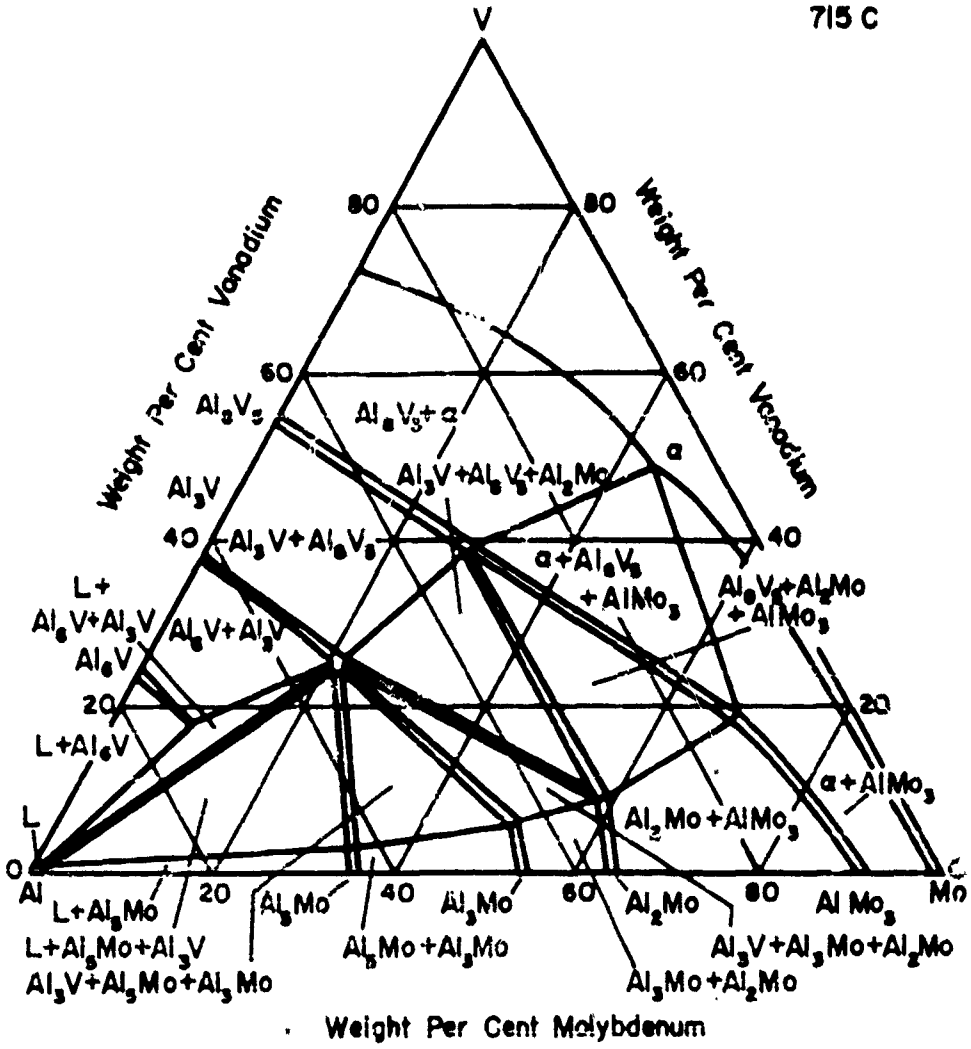
COLUMBIUM-TUNGSTEN-VANADIUM SYSTEM(206)



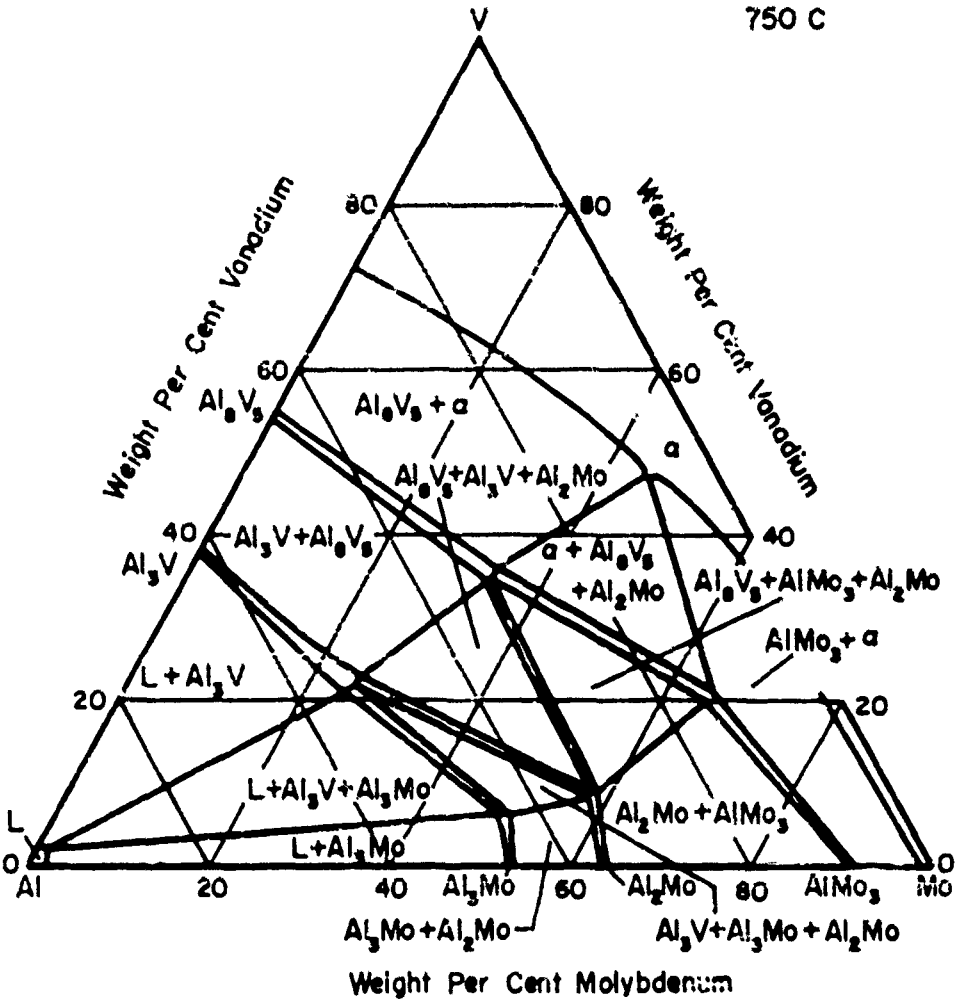

630 C
V
Weight Per Cent Vanadium
Weight Per Cent Vanadium
80
80
60
60
40
40
20
20
0
0
α
Al_8V_5
Al_8V_5+α
Al_3V
$Al_3V+Al_8V_5$
$Al_3V+Al_8V_5+Al_2Mo$
$Al_3V+Al_3Mo+Al_2Mo$
α+Al_8V_5+$AlMo_3$
Al_6V+Al_3V +Al_8Mo
Al_6V+Al_3V
Al_8V+Al_6V
Al_6V
$AlMo_3$+α
Al+$Al_{11}V$
$Al_{11}V$
Al_8V_5+Al_2Mo+$AlMo_3$
Al_3V+Al_8Mo +Al_3Mo
Al_3Mo+Al_2Mo
$Al_2Mo+AlMo_3$
$Al_{12}Mo$
Al
Al_8Mo
Al
$Al_{11}V+Al_6V+Al_{12}Mo$
$Al+Al_{11}V+Al_{12}Mo$
Al_3Mo
Al_2Mo
$AlMo_3$
Mo
$Al_5Mo+Al_6V+Al_{12}Mo$
Al_5Mo+Al_3Mo
Weight Per Cent Molybdenum

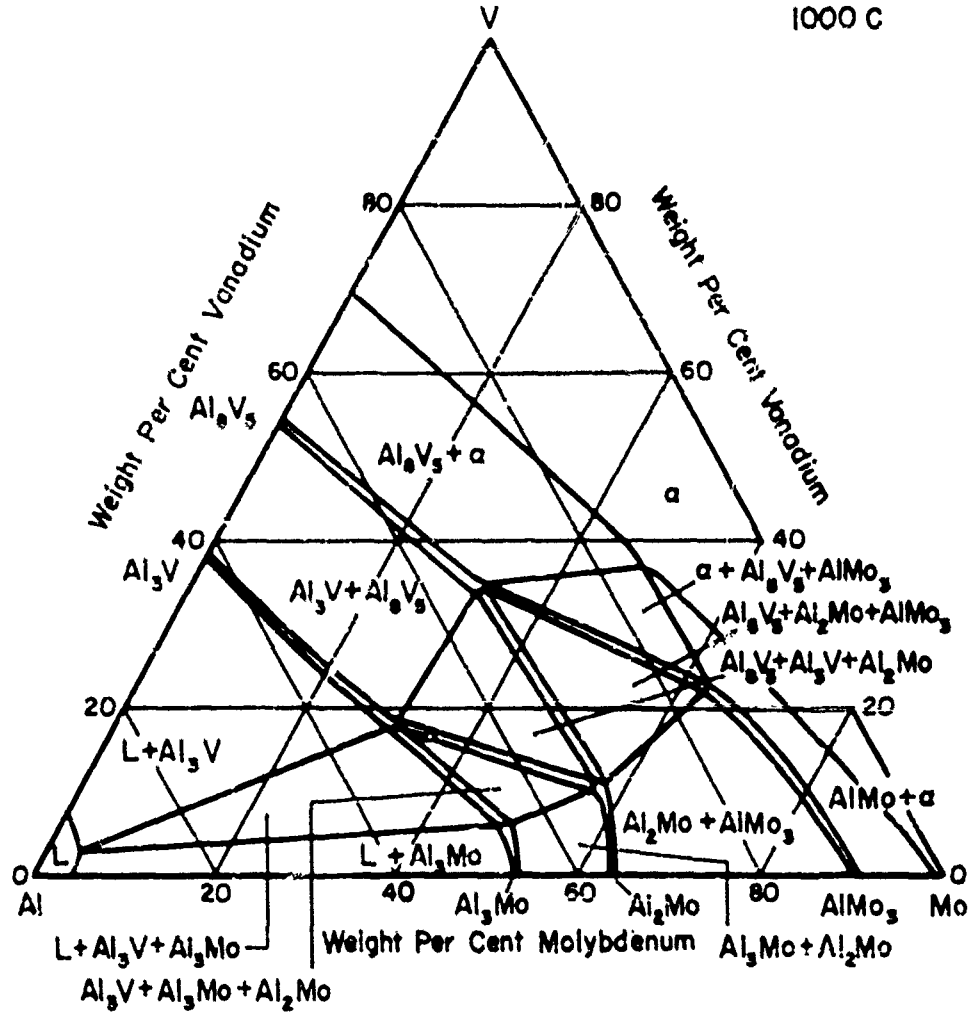

675 C
V
60
80
α
60
60
Al8V5
Al8V5+α
Weight Per Cent Vanadium
Weight Per Cent Vanadium
40
Al3V+Al8V5
α+Al8V5+AlMo3
40
Al11V+Al6V
+Al12Mo
Al3V
Al6V+Al3V
Al3V+Al3V5
+Al2Mo
Al6V
20
Al6V+
Al3V+Al5Mo
Al3V5+Al2Mo
+Al
AlMo3+α
20
Al11V
+Al6V
Al11V
L+Al11V
Al3V
+Al5Mo+Al3Mo
Al3V+Al2Mo+Al2Mo
Al5Mo
+Al2Mo
Al2Mo+Al3Mo
Al2Mo+AlMo3
AlMo3
0
L
0
Al
Al12Mo
20
Al5Mo
40
Al3Mo
60
Al2Mo
80
Mo
L+Al11V+Al12Mo
Al12Mo+Al5Mo
Al6V+Al12Mo+Al5Mo
Weight Per Cent Molybdenum

MOLYBDENUM-ALUMINUM-VANADIUM SYSTEM[211]

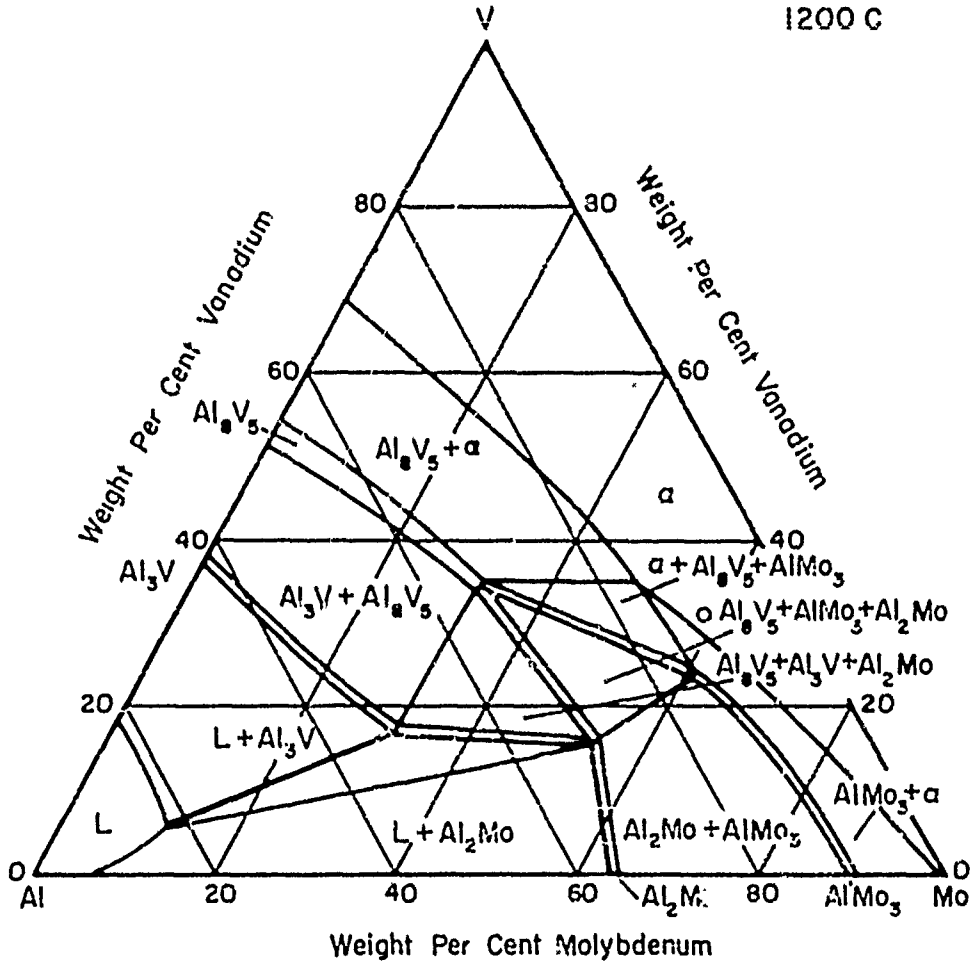


MOLYBDENUM-ALUMINUM-VANADIUM SYSTEM[211]

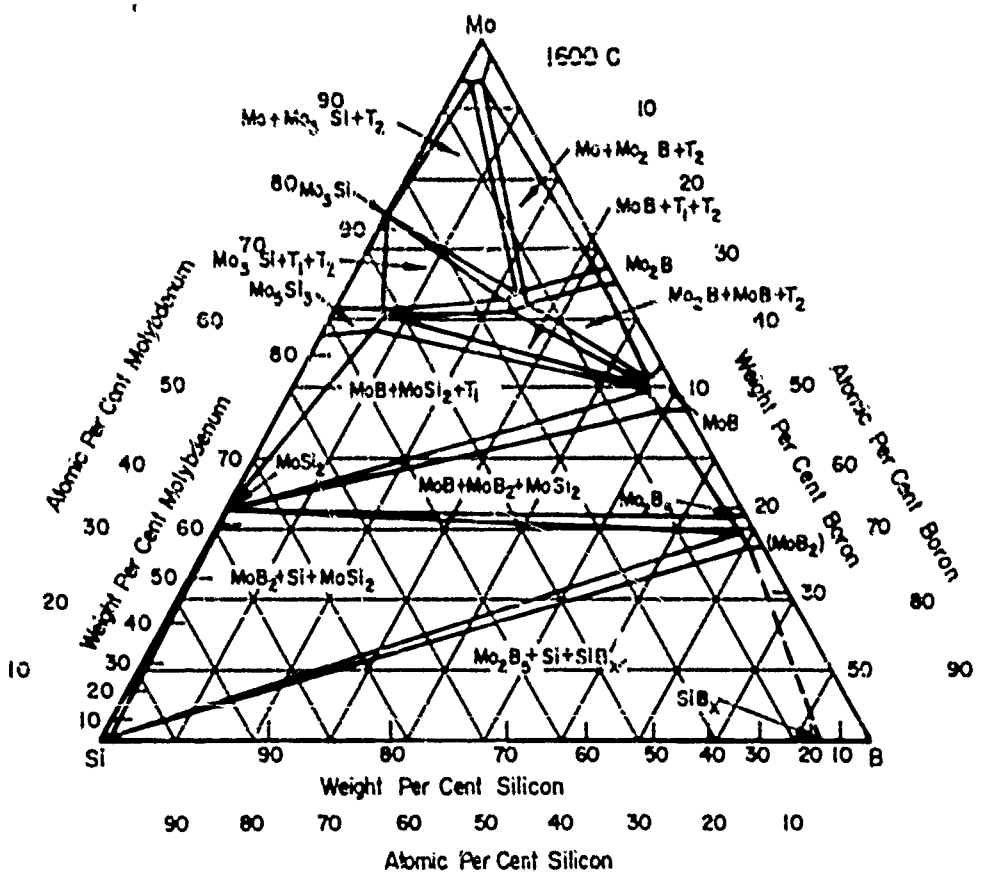



1000 C
V
Weight Per Cent Vanadium
Weight Per Cent Vanadium
80
60
40
20
0
Al_8V_5
$Al_8V_5+\alpha$
α
Al_3V
$Al_3V+Al_8V_5$
$\alpha+Al_8V_5+AlMo_3$
$Al_8V_5+Al_2Mo+AlMo_3$
$Al_8V_5+Al_3V+Al_2Mo$
$L+Al_3V$
L
$L+Al_3Mo$
$Al_2Mo+AlMo_3$
$AlMo+\alpha$
Al
20
40
Al_3Mo
60
Al_2Mo
80
$AlMo_3$
Mo
Weight Per Cent Molybdenum
$L+Al_3V+Al_3Mo$
$Al_3V+Al_3Mo+Al_2Mo$
Al_3Mo+Al_2Mo

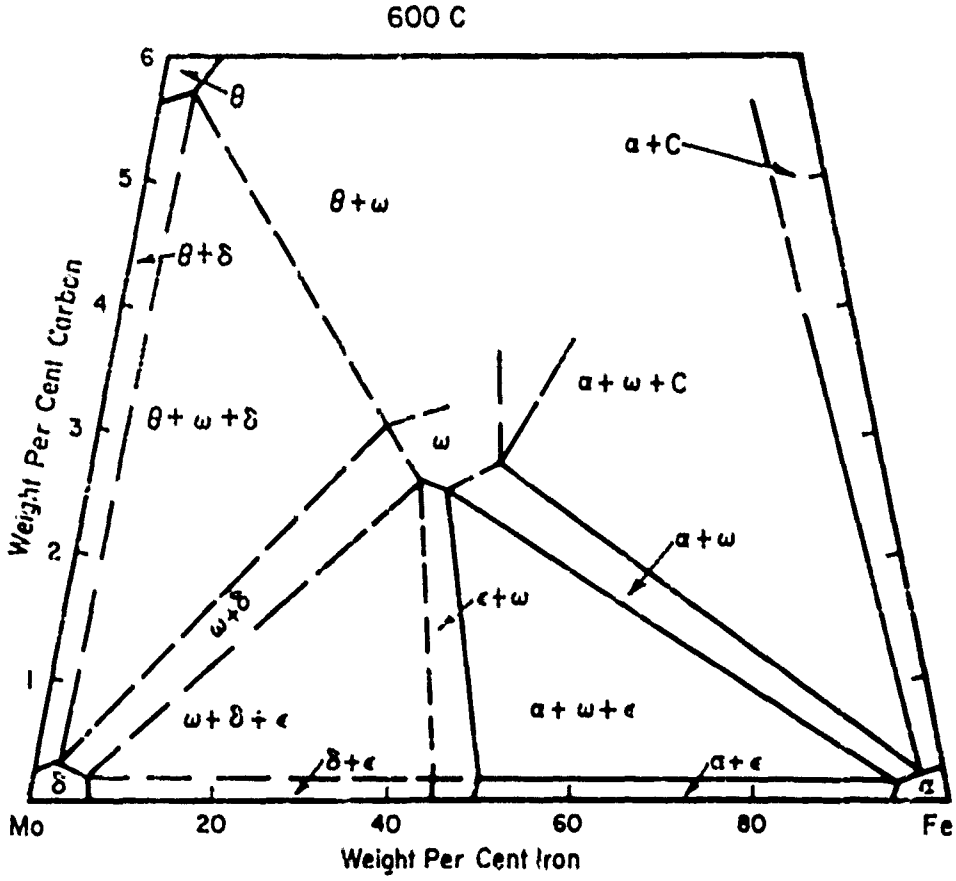
MOLYBDENUM-ALUMINUM-VANADIUM SYSTEM[211]

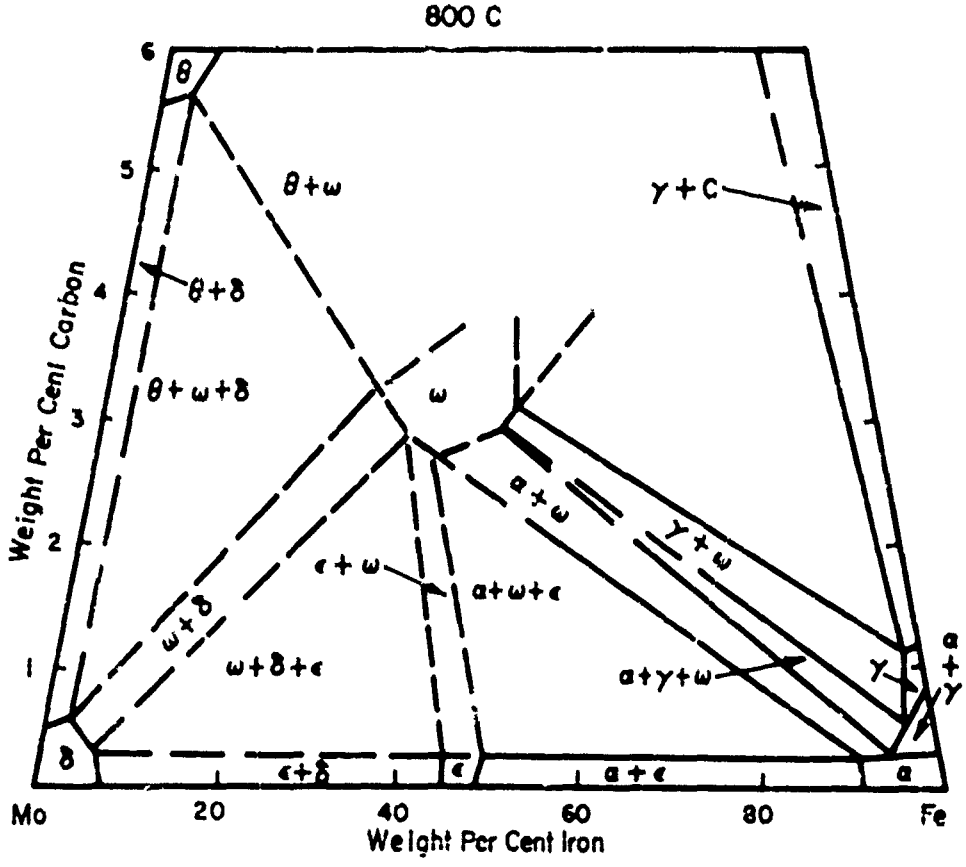


MOLYBDENUM-BORON-SILICON SYSTEM[212]

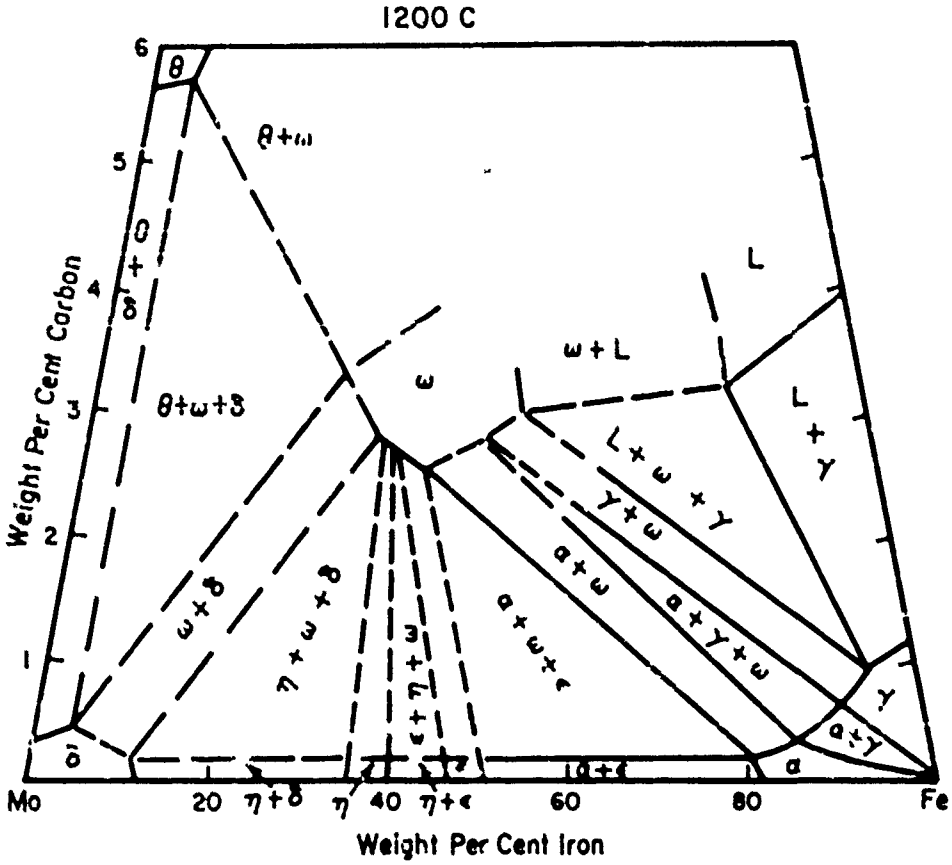


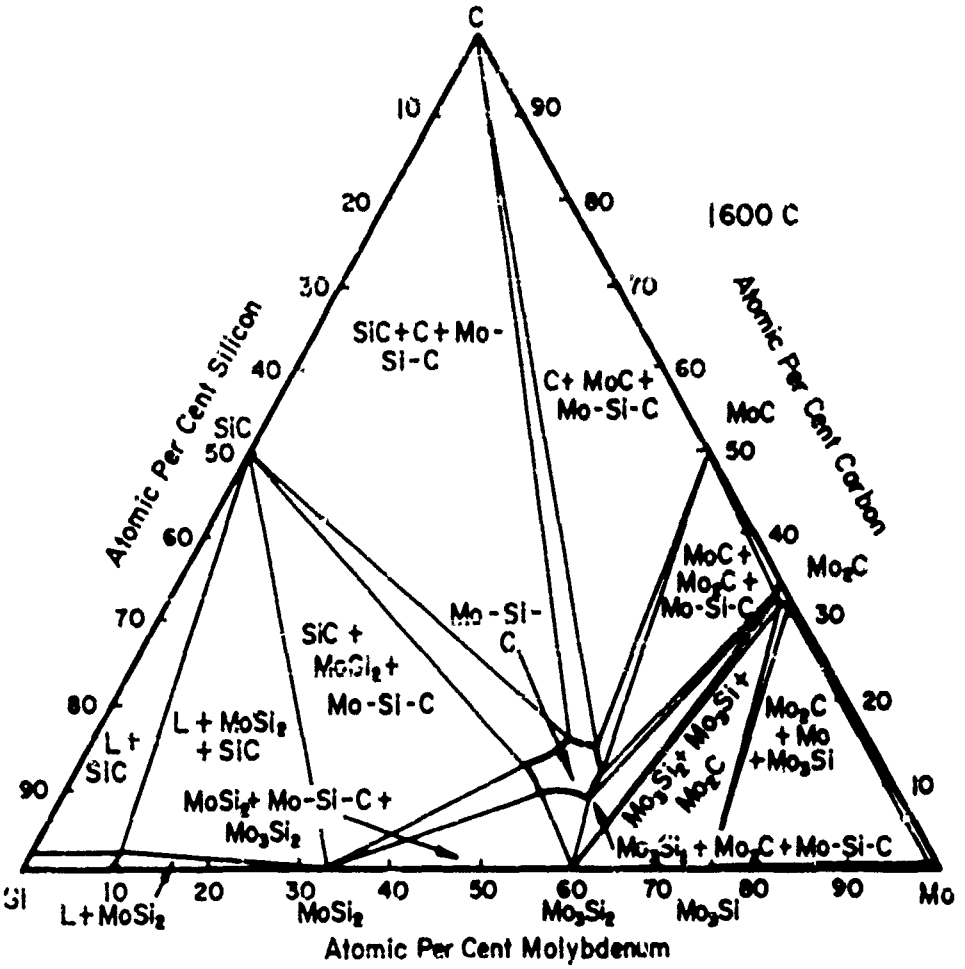
MOLYBDENUM-CARBON-IRON SYSTEM[213]



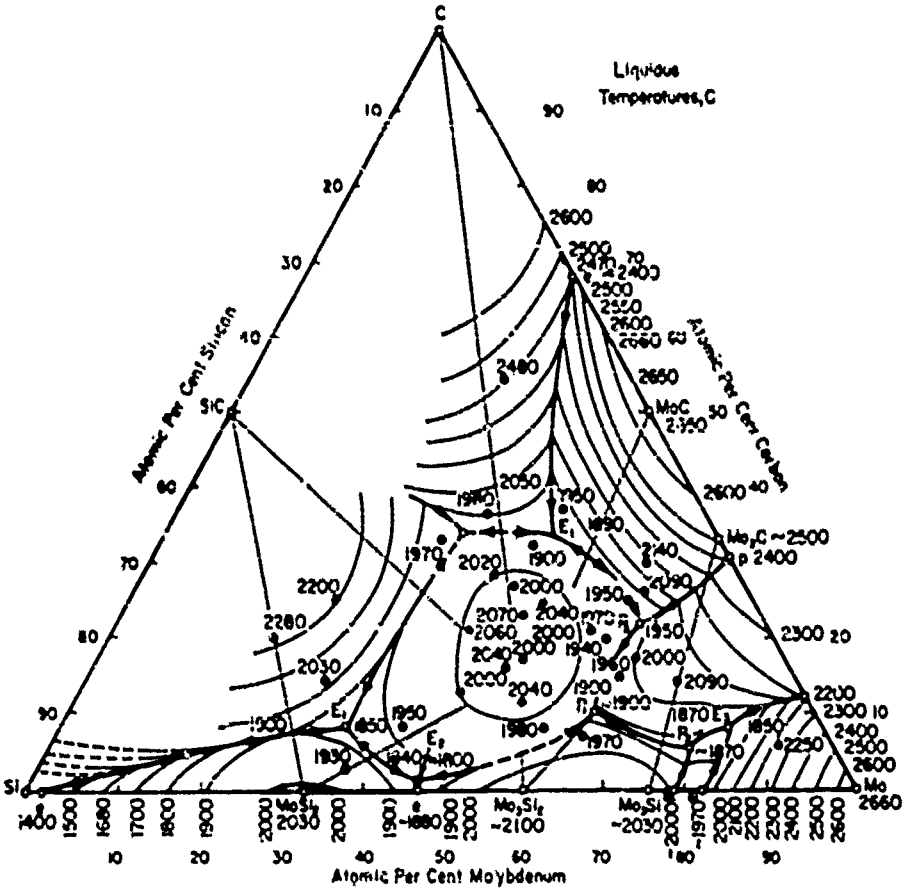

800 C
θ
θ+ω
γ+C
θ+δ
θ+ω+δ
ω
α+ε
γ+ω
ε+ω
α+ω+ε
ω+δ
ω+δ+ε
α+γ+ω
γ
α+γ
δ
ε+δ
ε
α+ε
α
Weight Per Cent Carbon
Mo
20
40
60
80
Fe
Weight Per Cent Iron

MOLYBDENUM-CARBON-IRON SYSTEM[213]

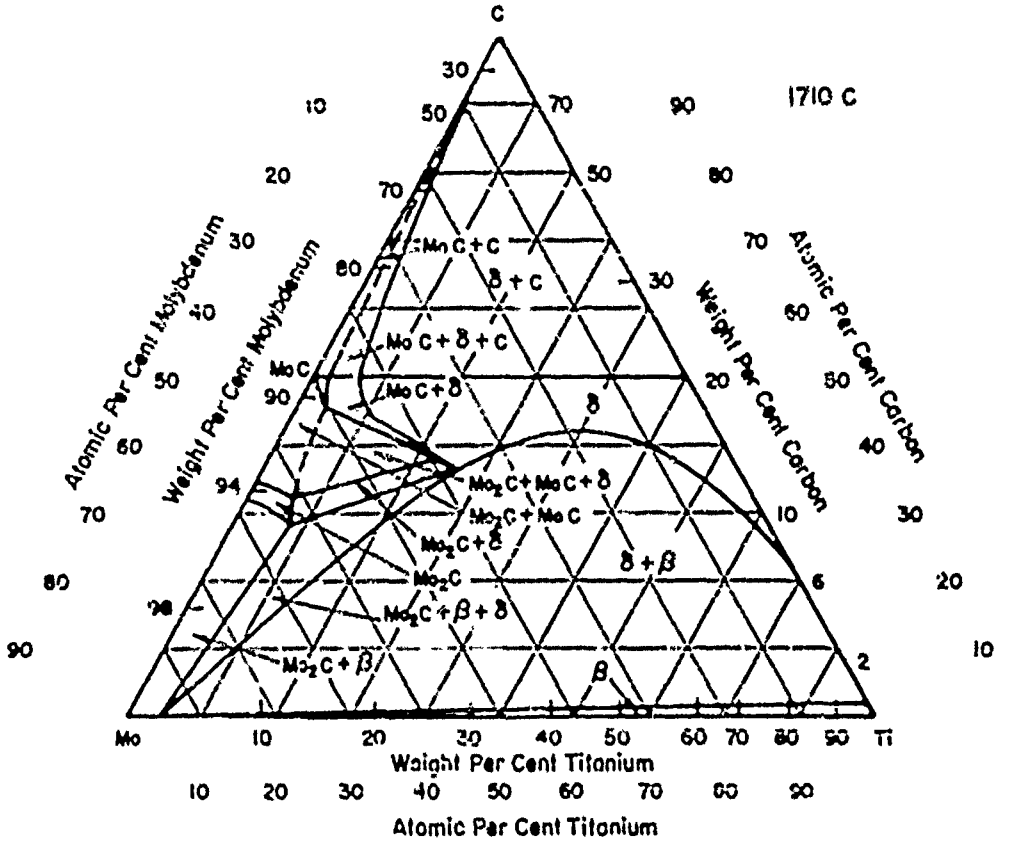



C
1600 C
Atomic Per Cent Silicon
Atomic Per Cent Carbon
Atomic Per Cent Molybdenum
SiC
MoC
Mo2C
SiC+C+Mo-Si-C
C+MoC+Mo-Si-C
MoC+Mo2C+Mo-Si-C
Mo-Si-C
SiC+MoSi2+Mo-Si-C
L+SiC
L+MoSi2+SiC
MoSi2+Mo-Si-C+Mo3Si2
Mo2C+Mo+Mo3Si
Mo3Si2+Mo2C
Mo3Si+Mo2C
Mo3Si2+Mo2C+Mo-Si-C
Si
L+MoSi2
MoSi2
Mo3Si2
Mo3Si
Mo

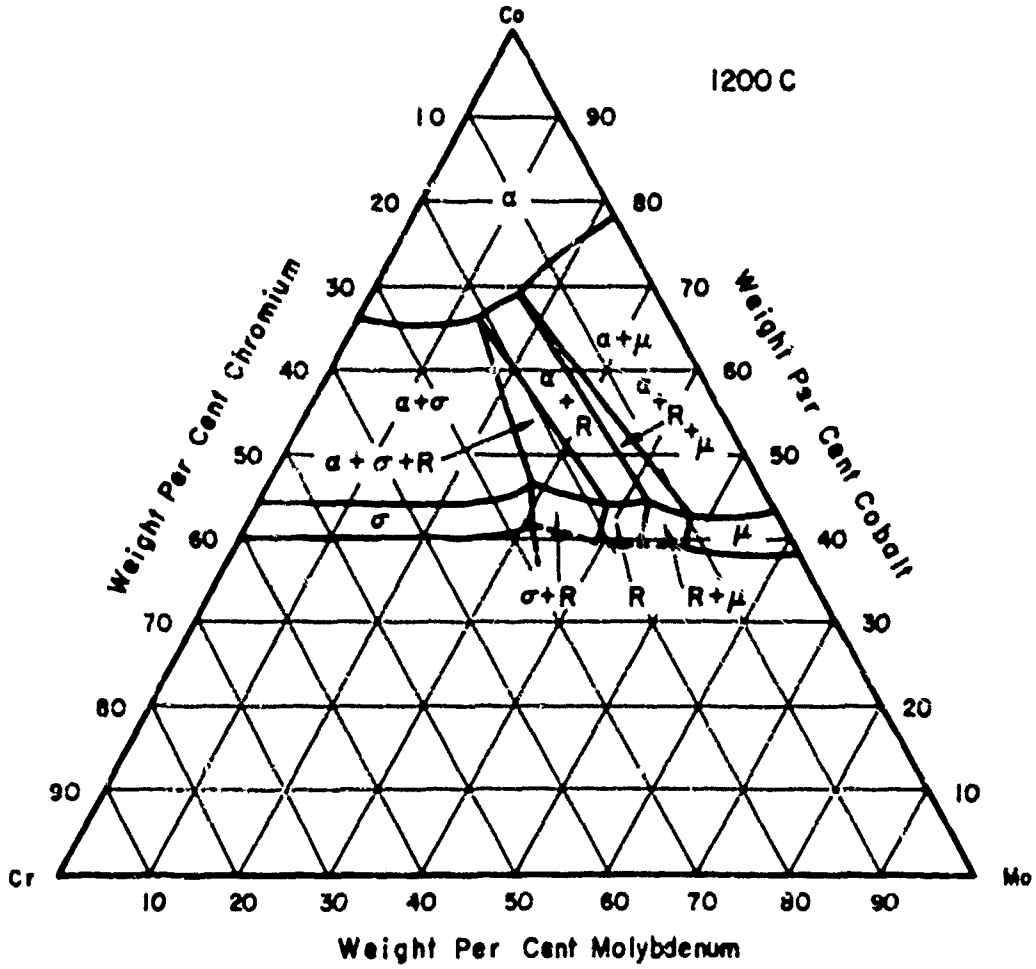
MOLYBDENUM-CARBON-SILICON SYSTEM[214]



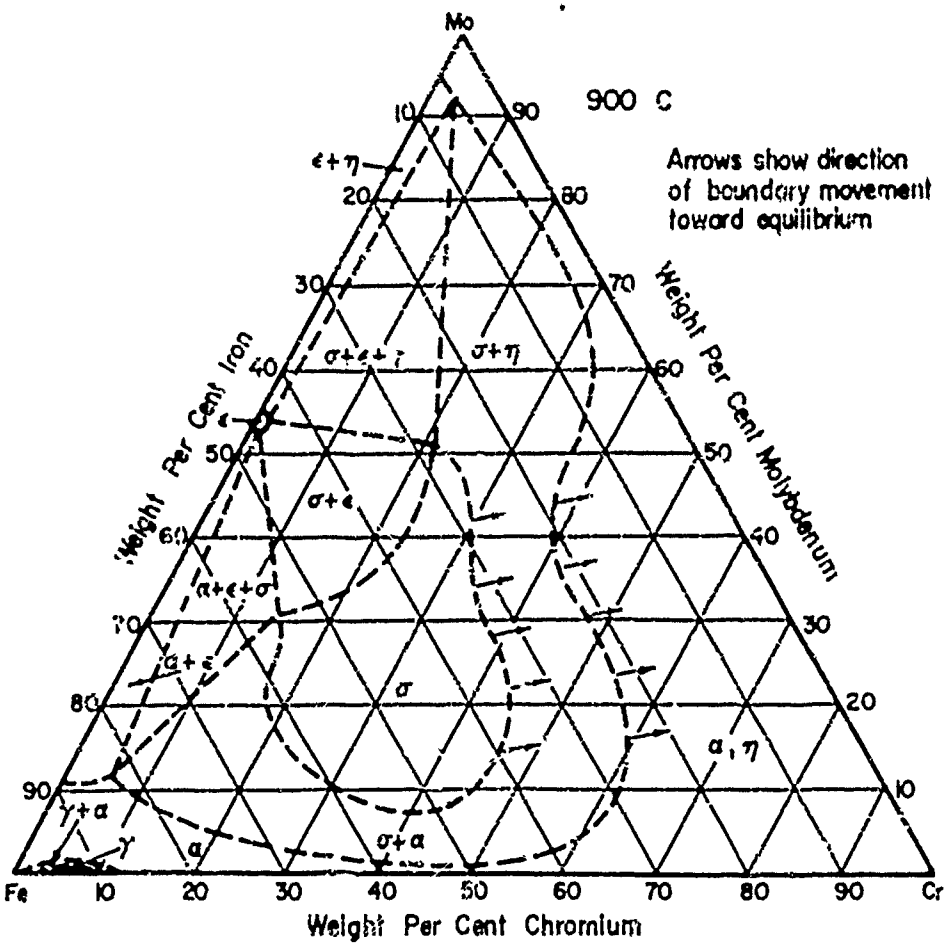
MOLYBDENUM-CARBON-TITANIUM SYSTEM[219]



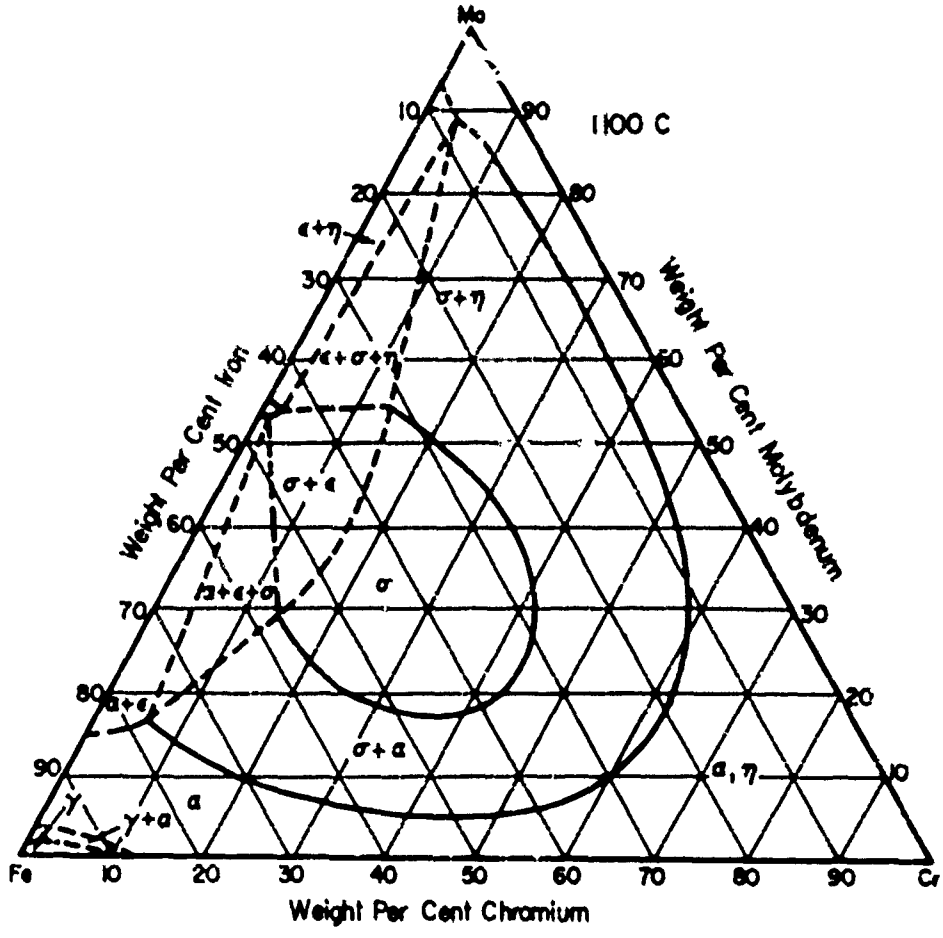
MOLYBDENUM-CHROMIUM-COBALT SYSTEM(226)



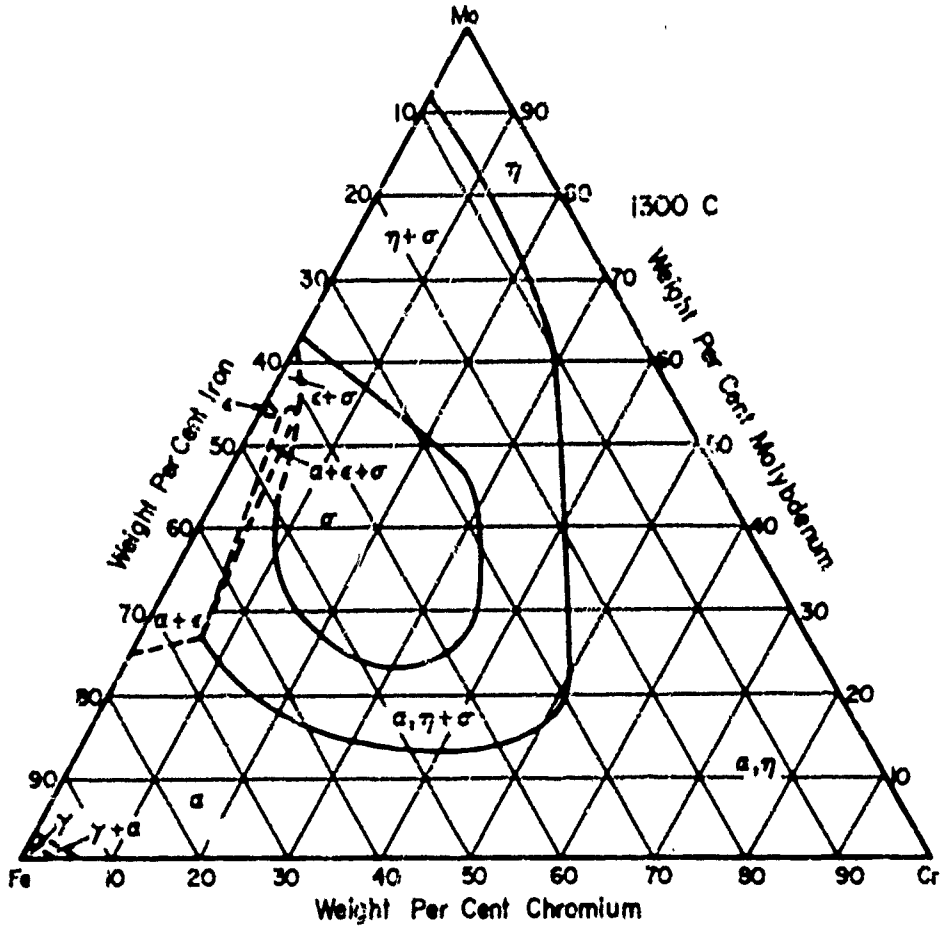
MOLYBDENUM-CHROMIUM-IRON SYSTEM[220]



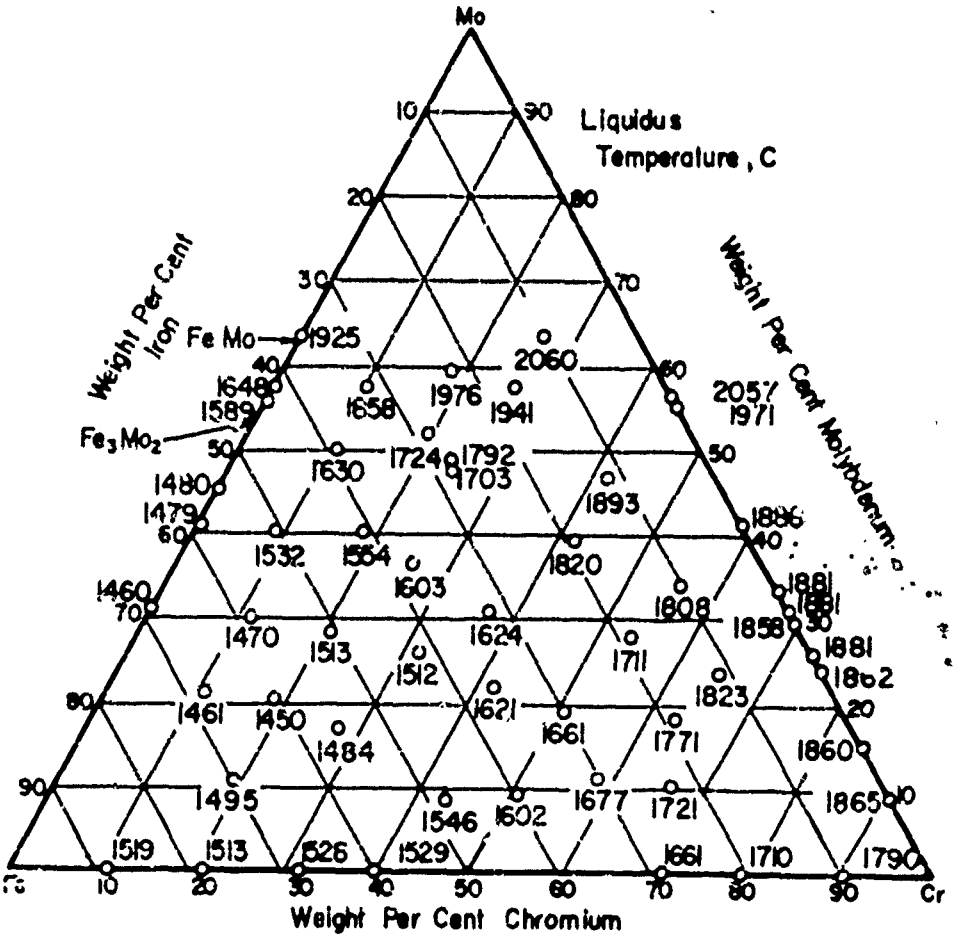
MOLYBDENUM-CHROMIUM-IRON SYSTEM[216]



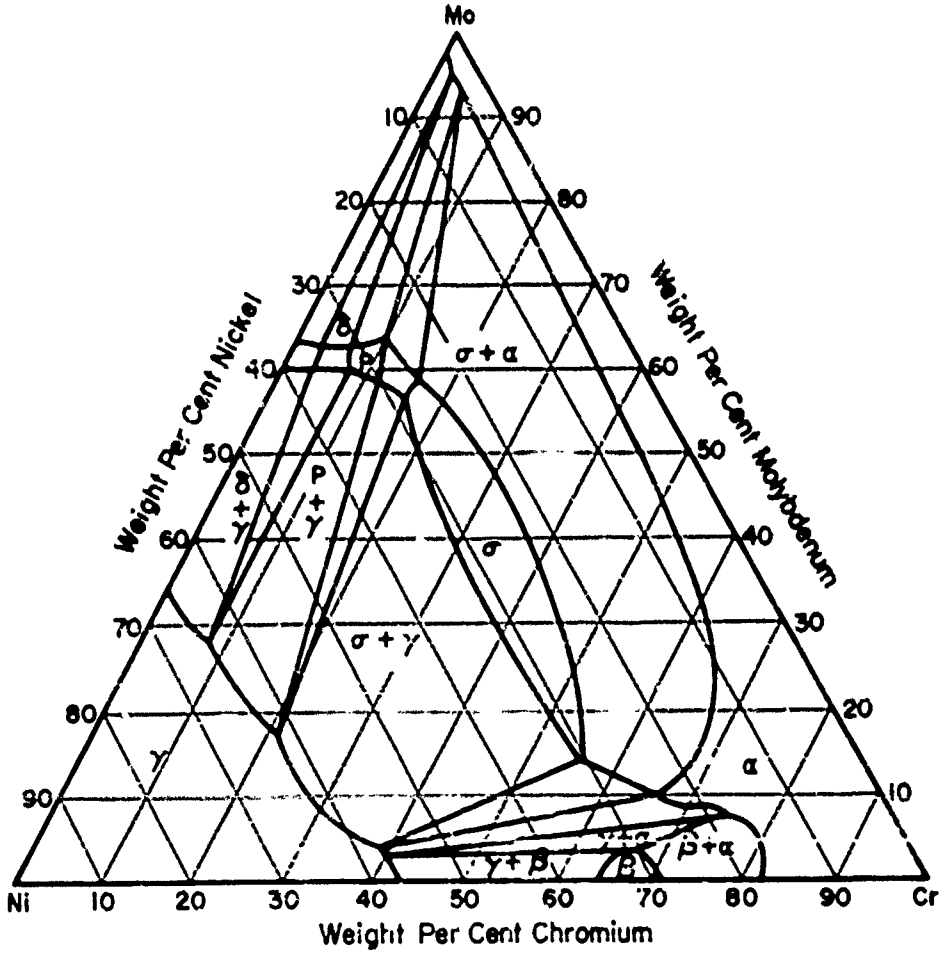
MOLYBDENUM-CHROMIUM-IRON SYSTEM[216]



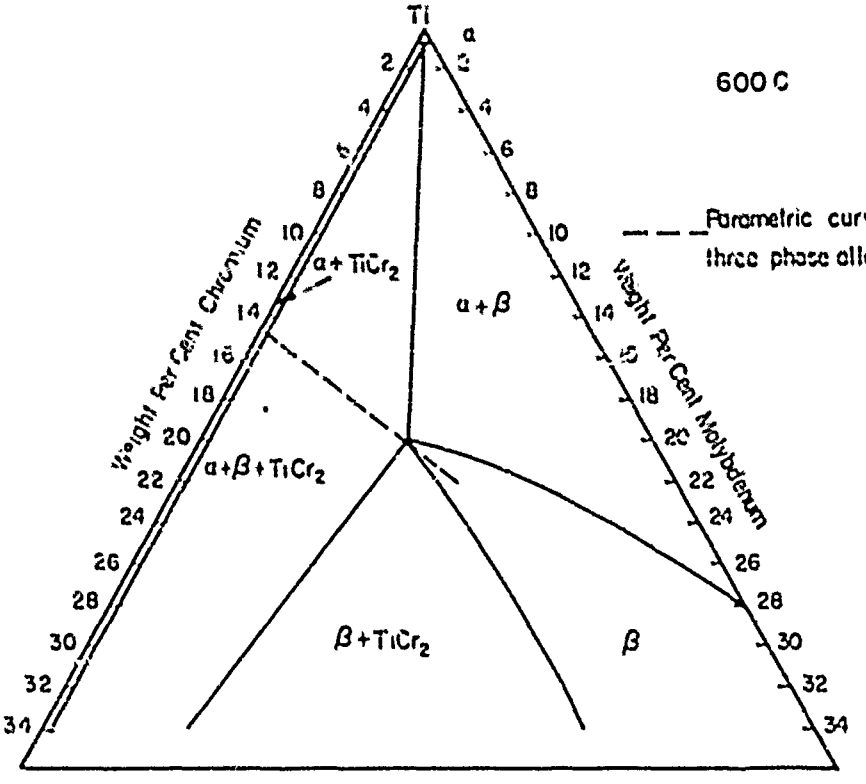
MOLYBDENUM-CHROMIUM-IRON SYSTEM[216]



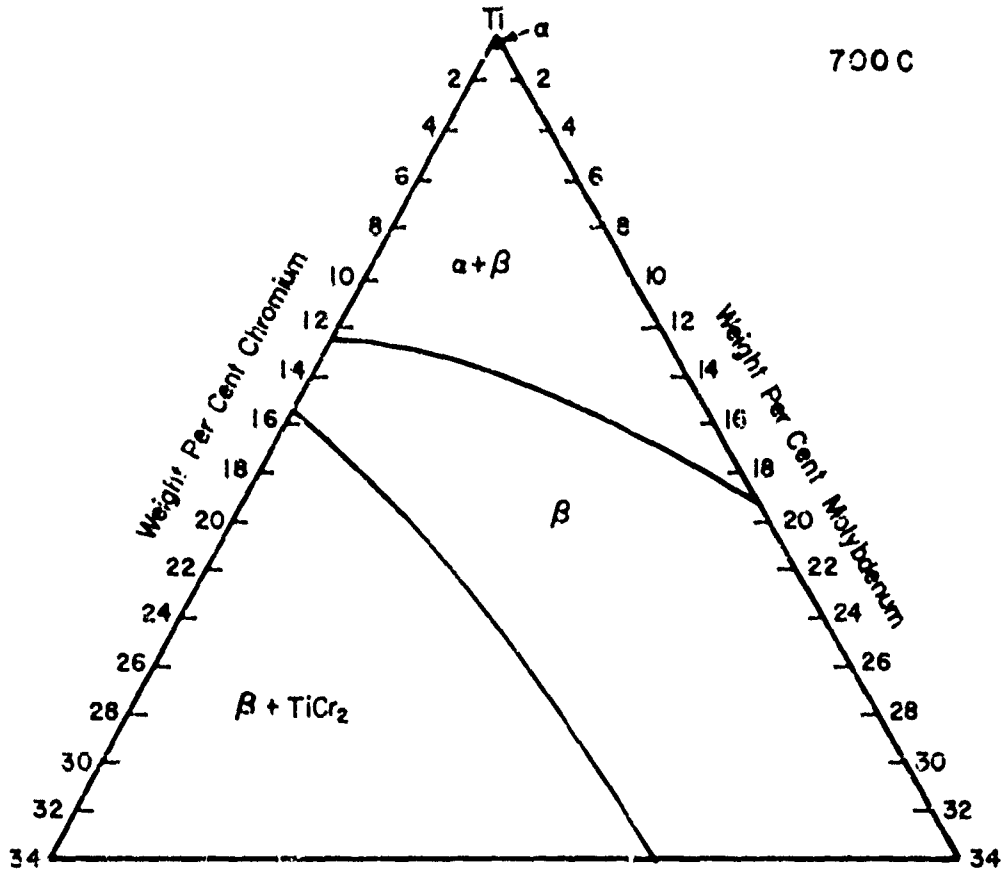
MOLYBDENUM-CHROMIUM-NICKEL SYSTEM[64]



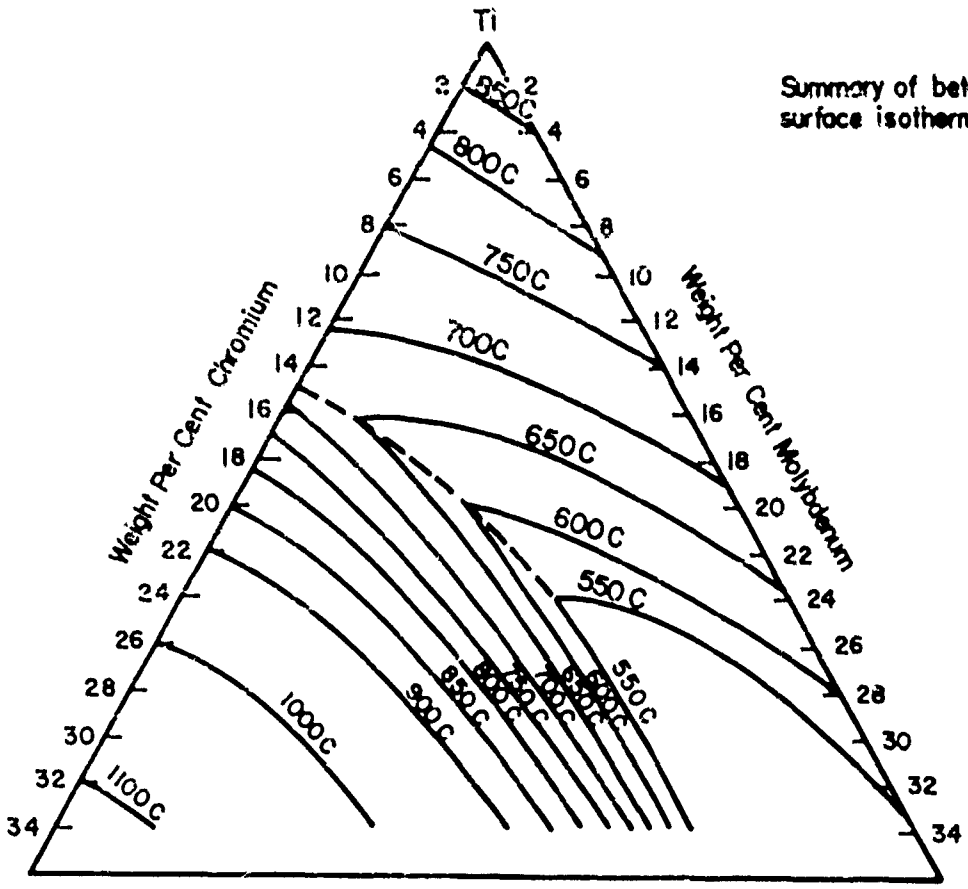
MOLYBDENUM-CHROMIUM-TITANIUM SYSTEM[217]



MOLYBDENUM-CHROMIUM-TITANIUM SYSTEM(217)

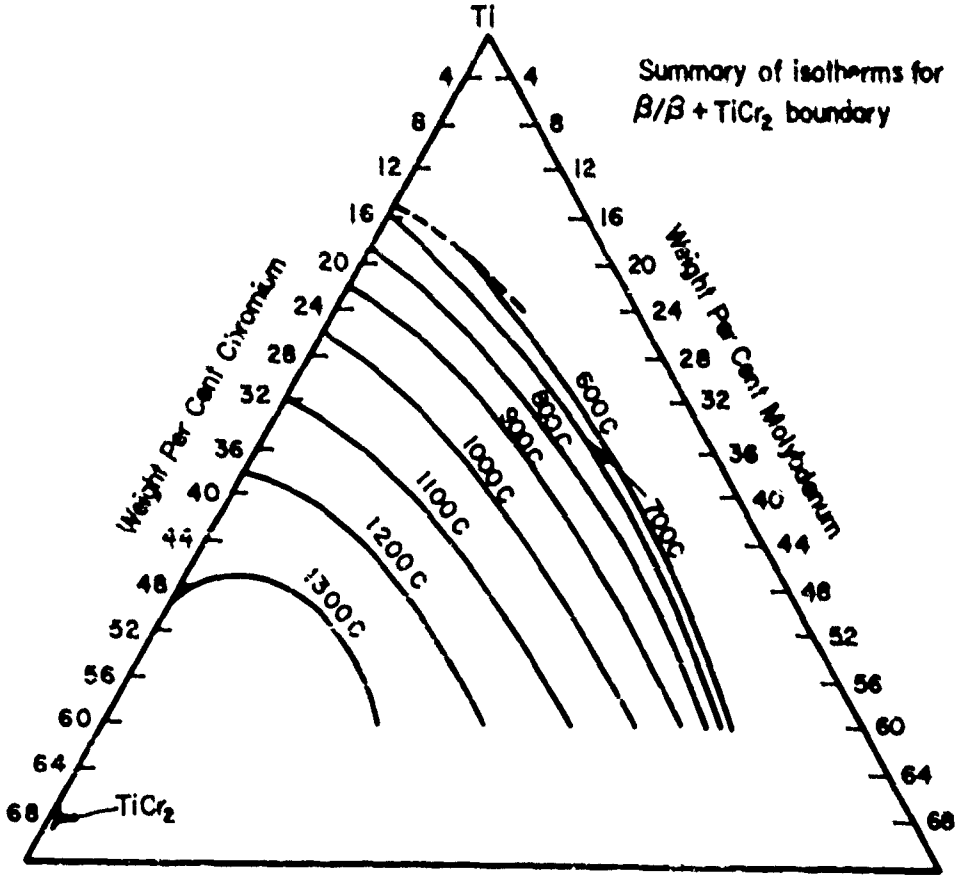


MOLYBDENUM-CHROMIUM-TITANIUM SYSTEM[217]

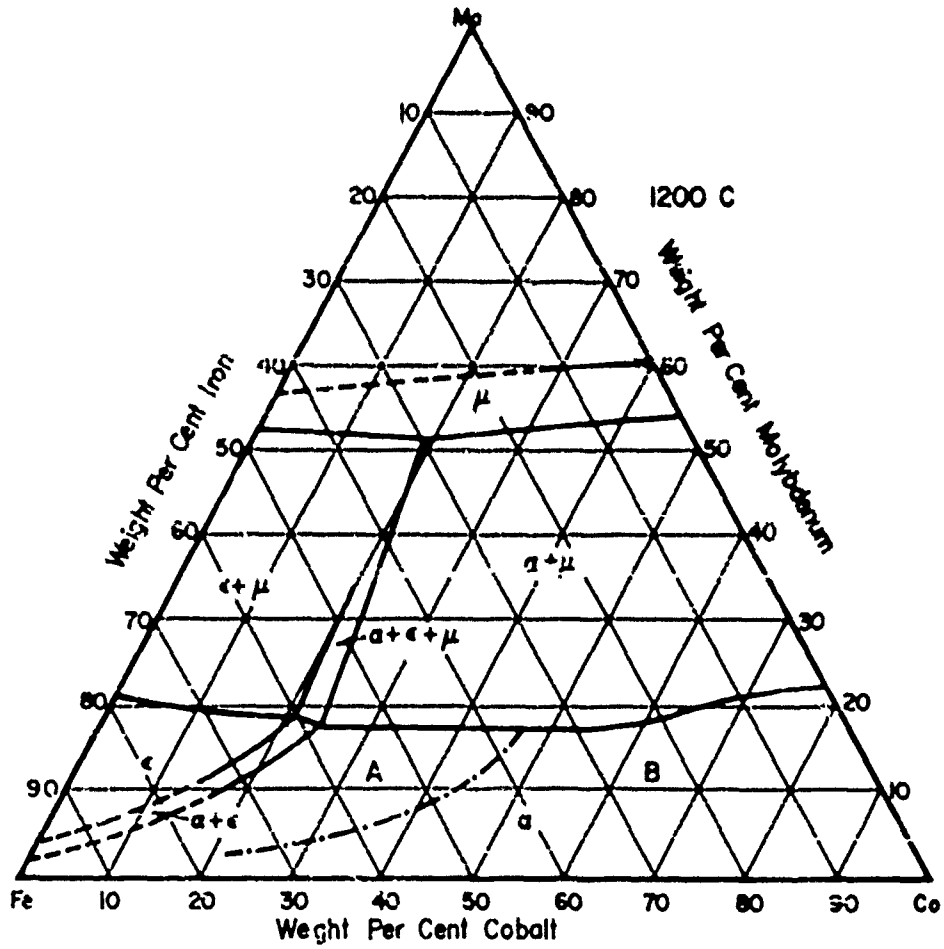


Summary of beta surface isotherms

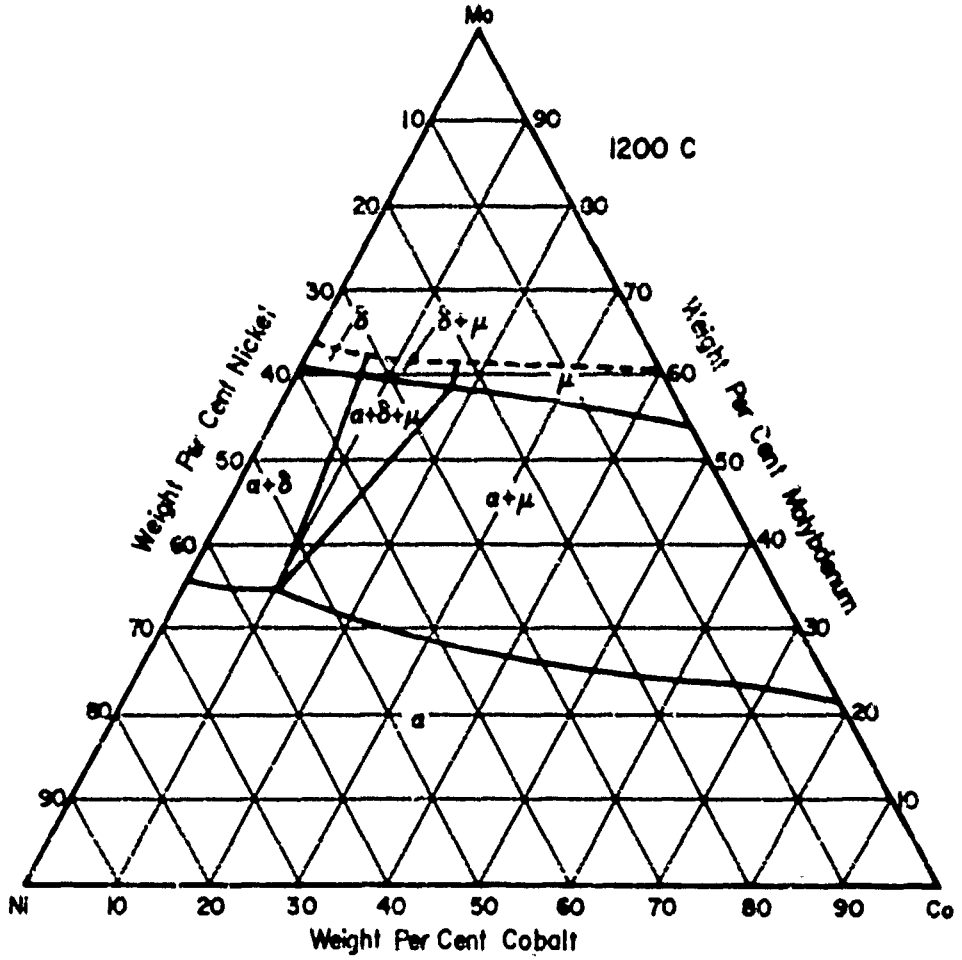
MOLYBDENUM-CHROMIUM-TITANIUM SYSTEM[217]

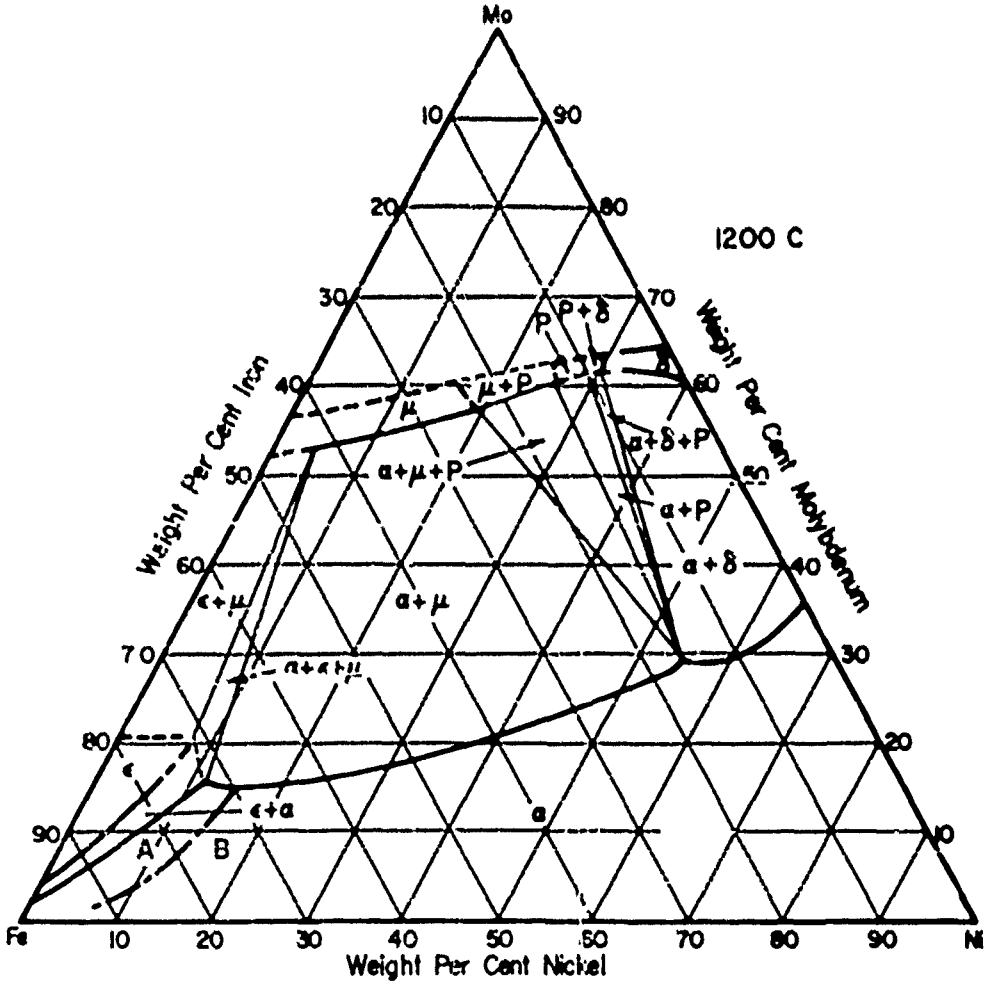


MOLYBDENUM-COBALT-IRON SYSTEM[227]

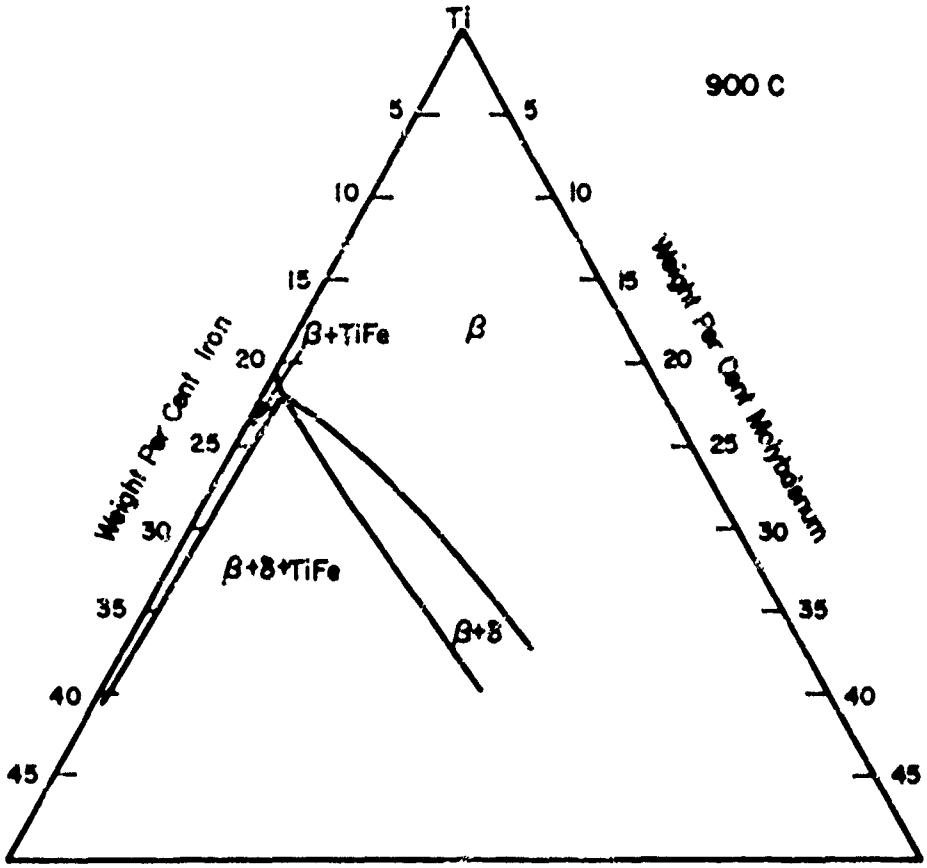


MOLYBDENUM-COBALT-NICKEL SYSTEM[227]

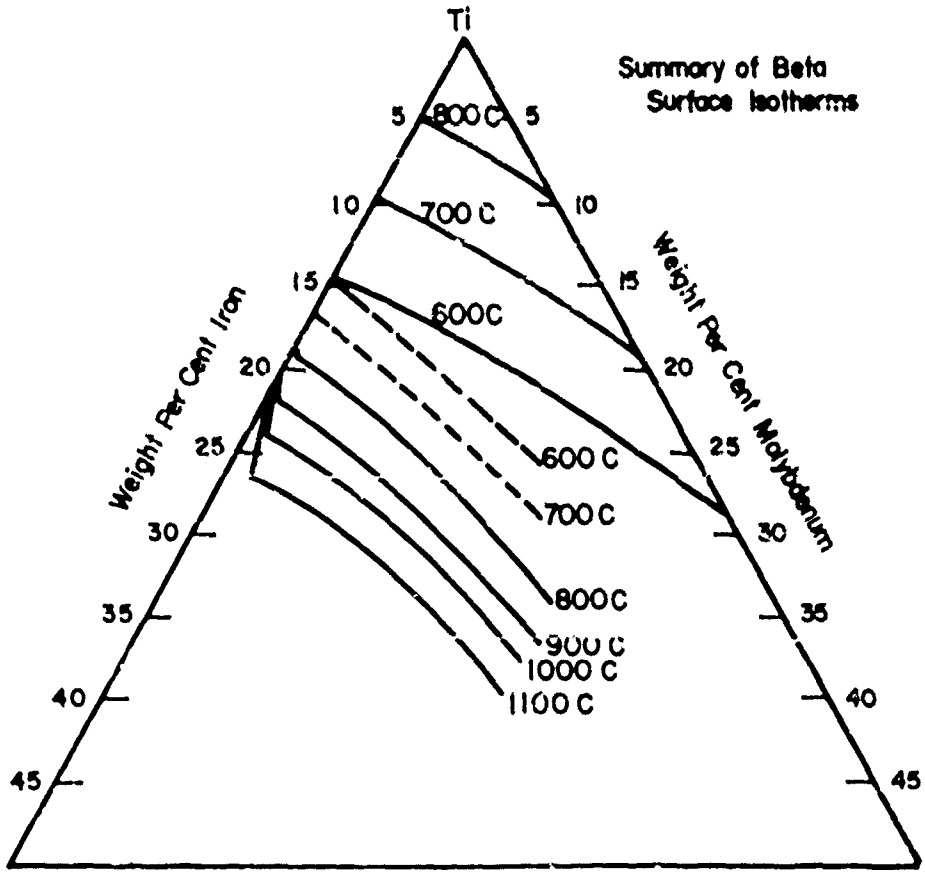



Mo
1200 C
Weight Per Cent Iron
Weight Per Cent Molybdenum
Weight Per Cent Nickel
Fe
Ni
A
B
μ
μ+P
P
P+δ
α+δ+P
α+P
α+δ
α+μ+P
ε+μ
α+μ
α+ε+μ
ε
ε+α
α

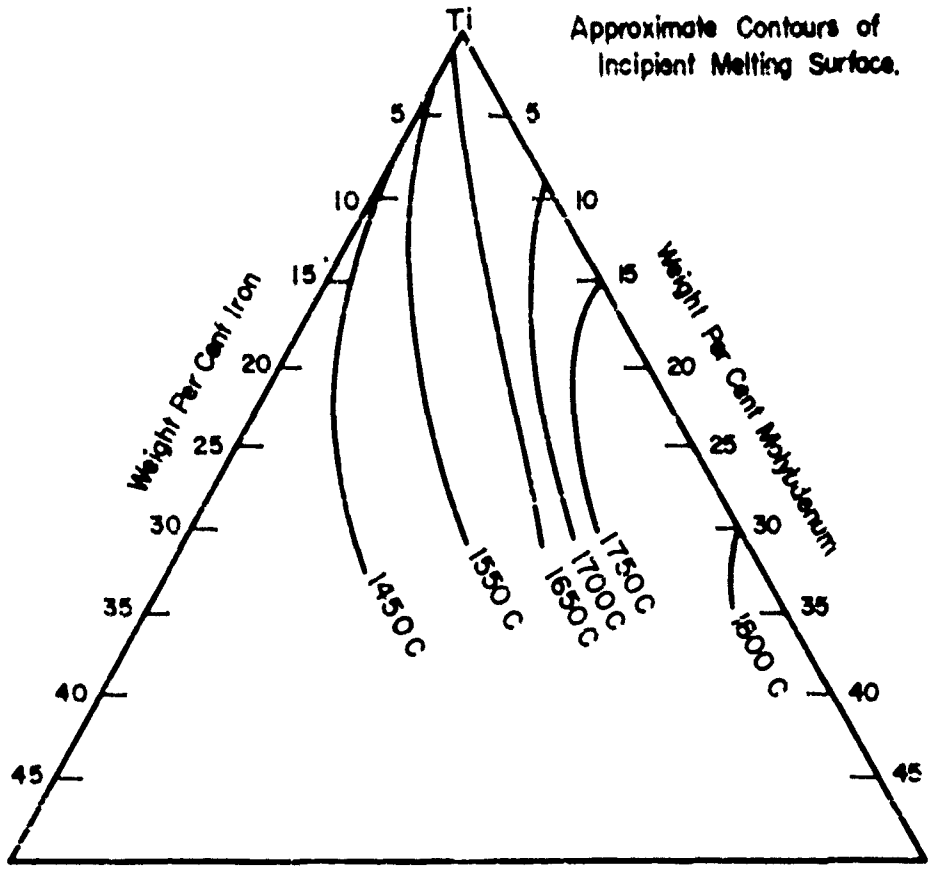
MOLYBDENUM-IRON-TITANIUM SYSTEM(217)



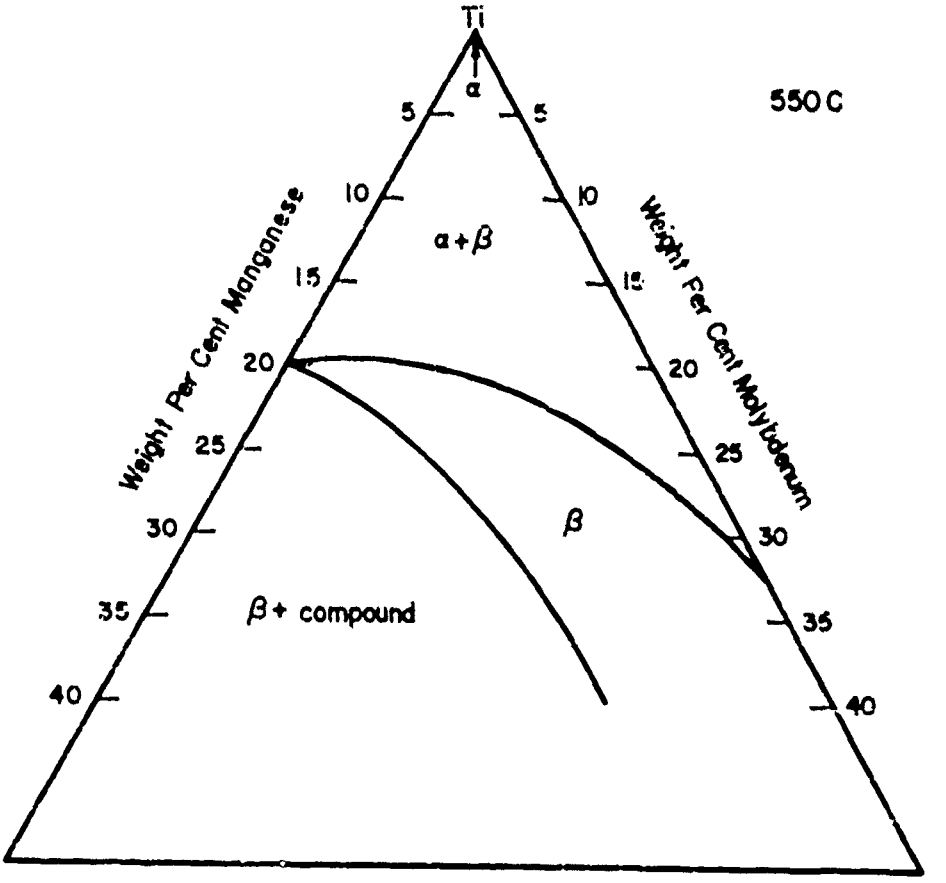
MOLYBDENUM-IRON-TITANIUM SYSTEM[217]



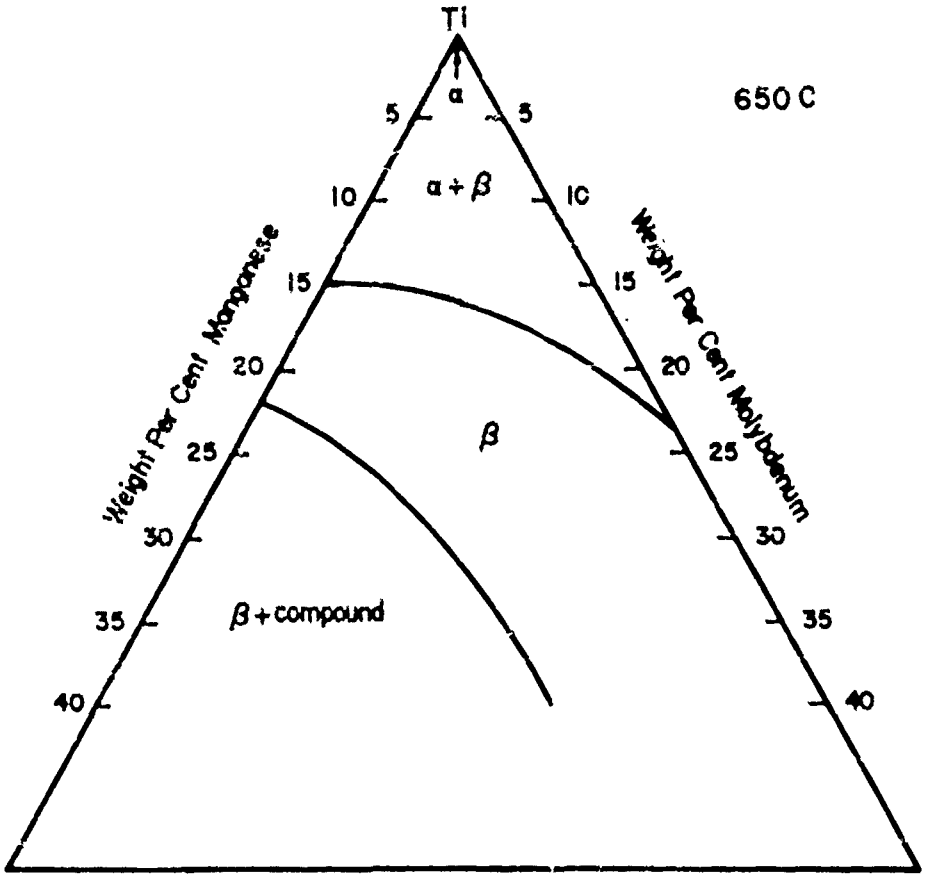
MOLYBDENUM-IRON-TITANIUM SYSTEM[217]



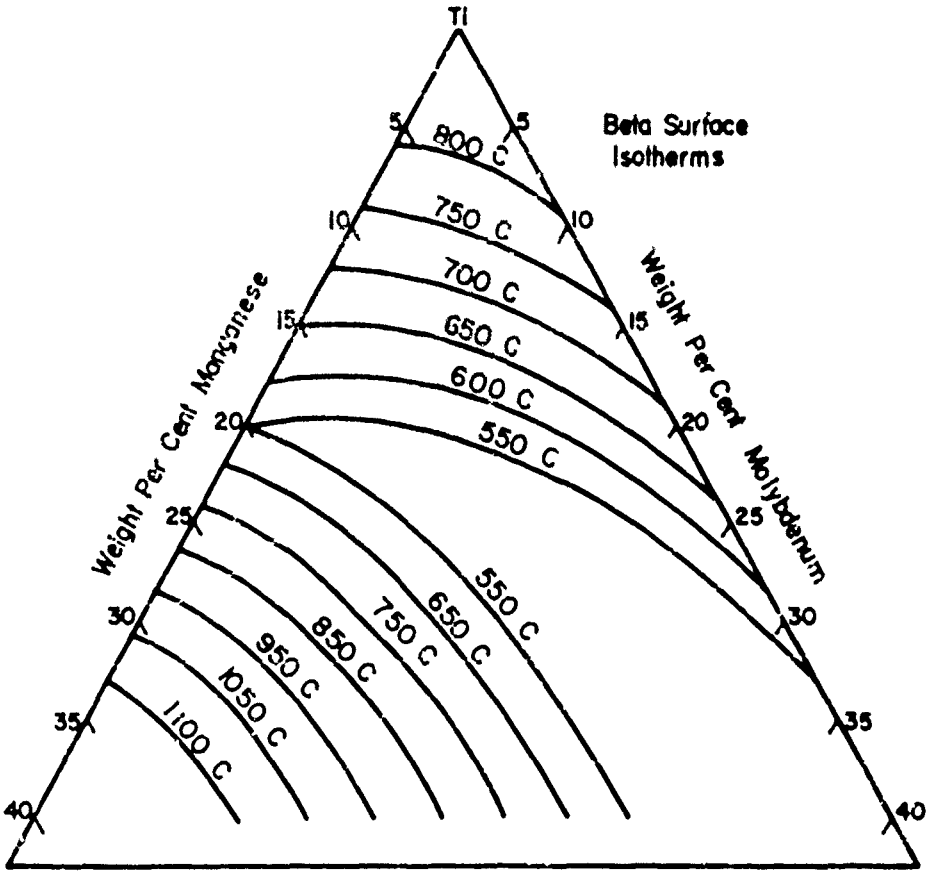
MOLYBDENUM-MANGANESE-TITANIUM SYSTEM(217)



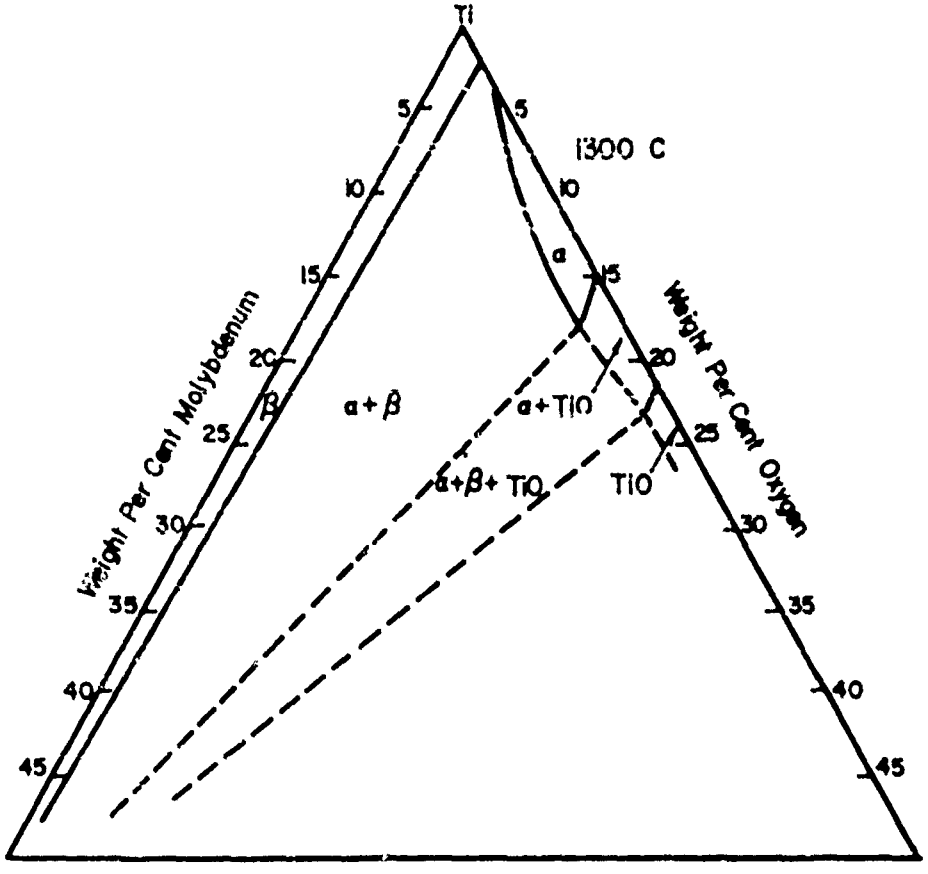
MOLYBDENUM-MANGANESE-TITANIUM SYSTEM[217]

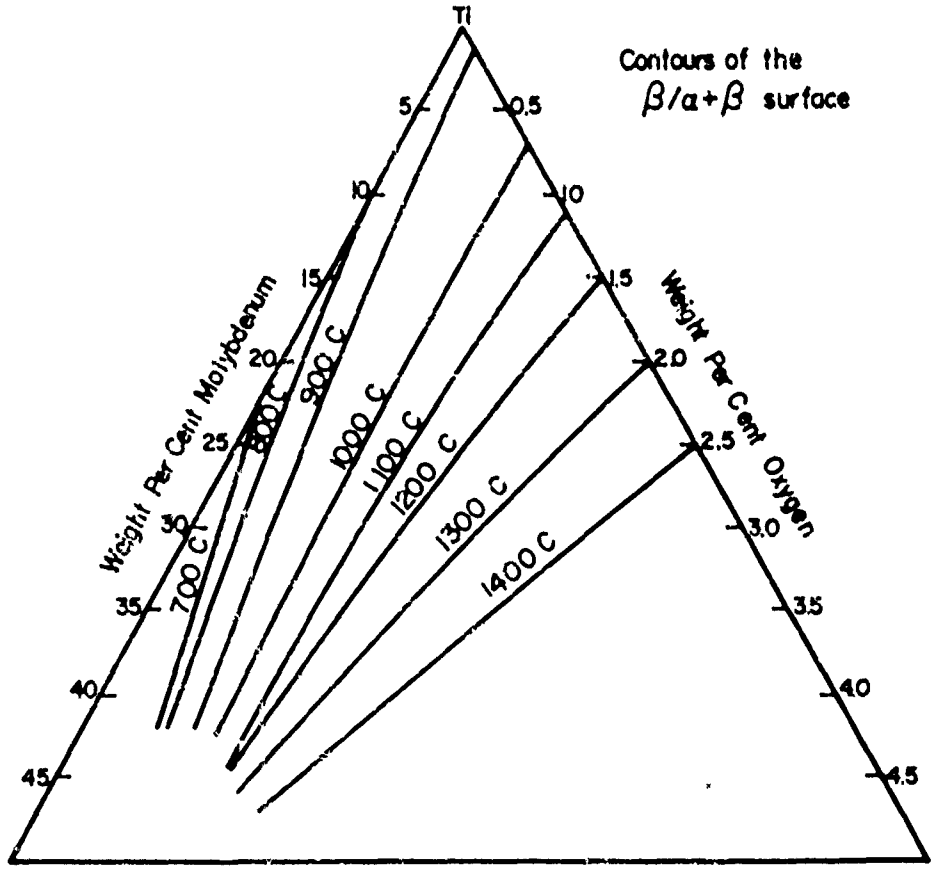


MOLYBDENUM-MANGANESE-TITANIUM SYSTEM[217]

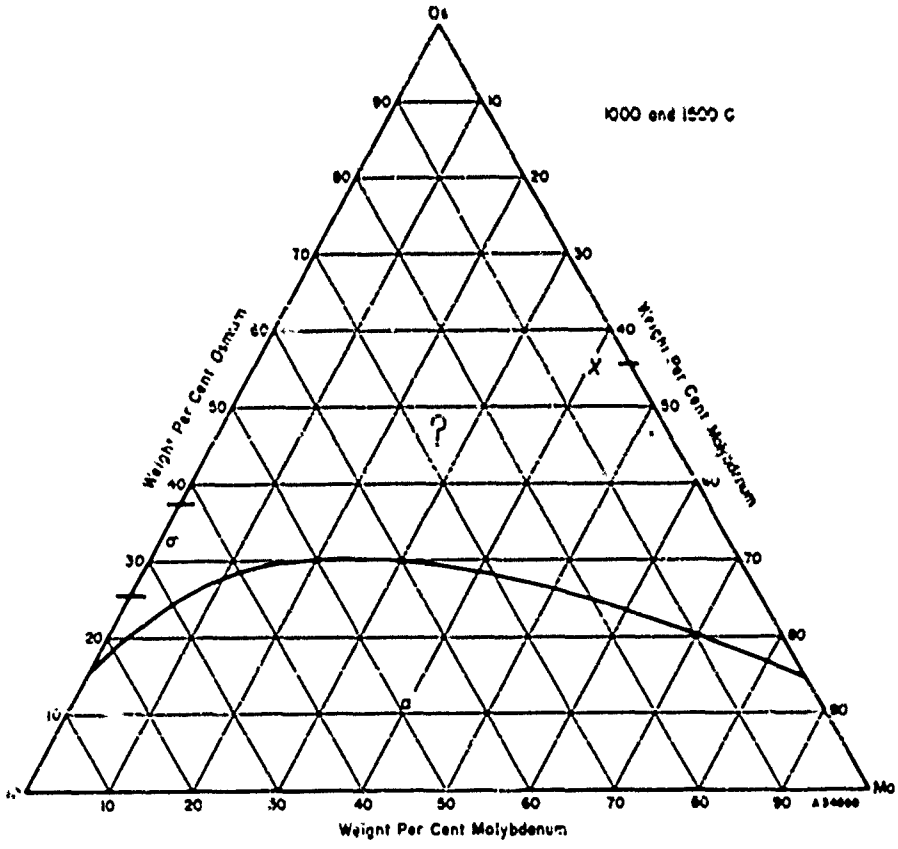


MOLYBDENUM-OXYGEN-TITANIUM SYSTEM[217]

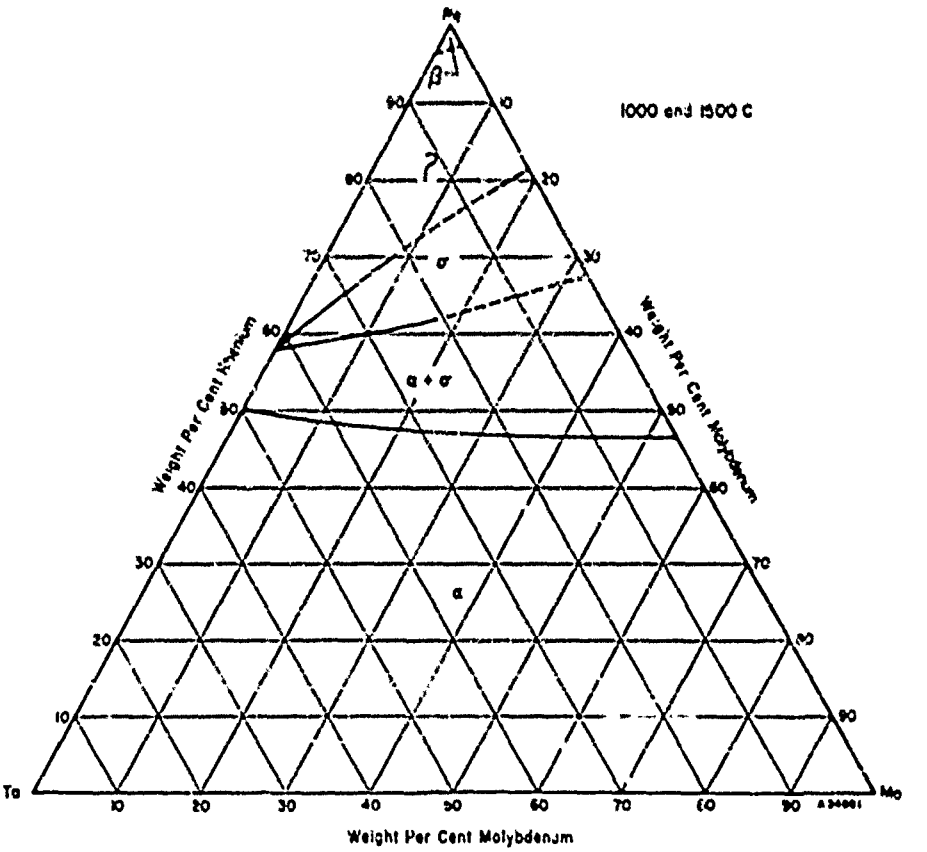



Ti
Contours of the
β/α+β surface
Weight Per Cent Molybdenum
Weight Per Cent Oxygen
5
10
15
20
25
30
35
40
45
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
700 C
800 C
900 C
1000 C
1100 C
1200 C
1300 C
1400 C

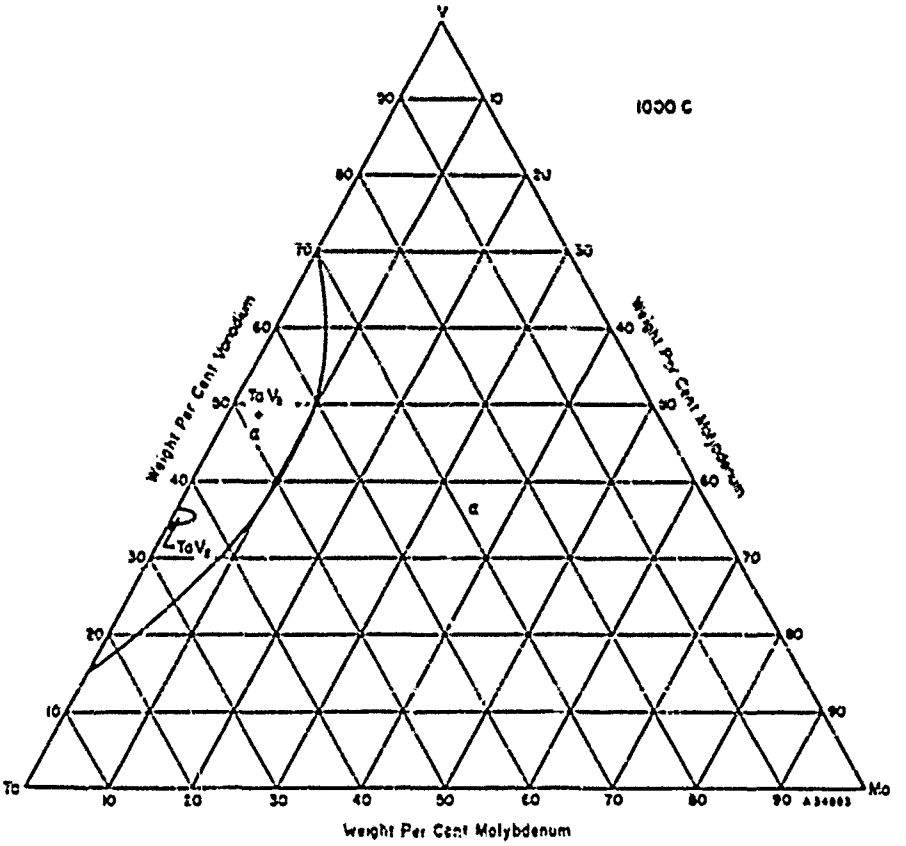
MOLYBDENUM-TANTALUM-OSMIUM SYSTEM[206]



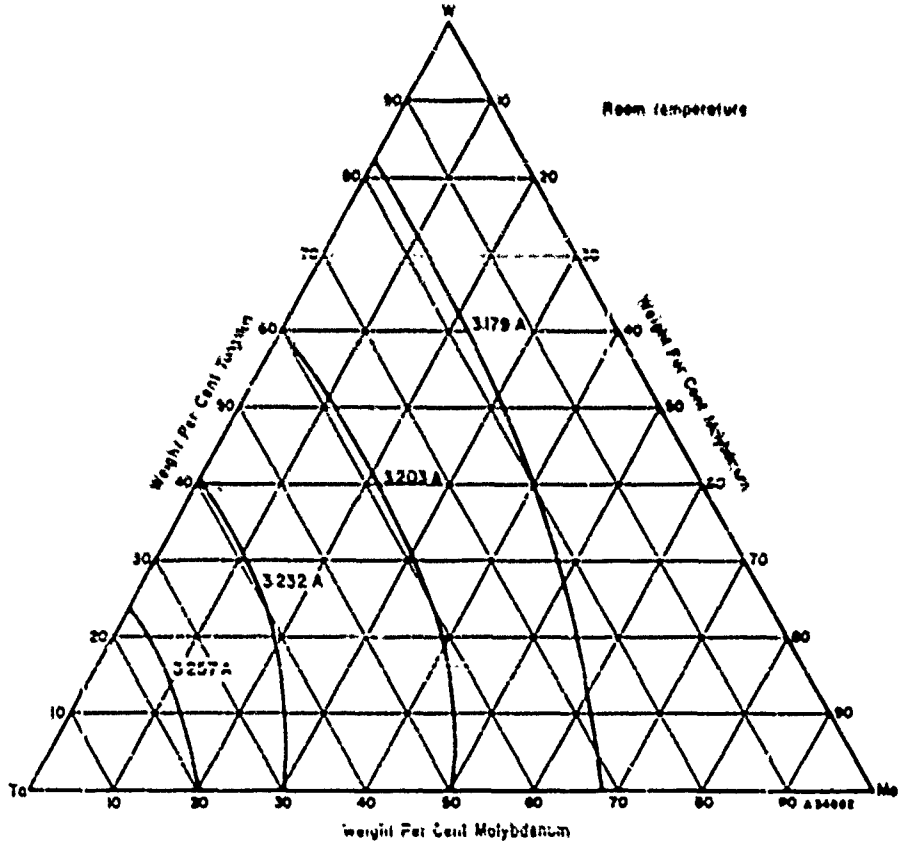
MOLYBDENUM-TANTALUM-RHENIUM SYSTEM(206)



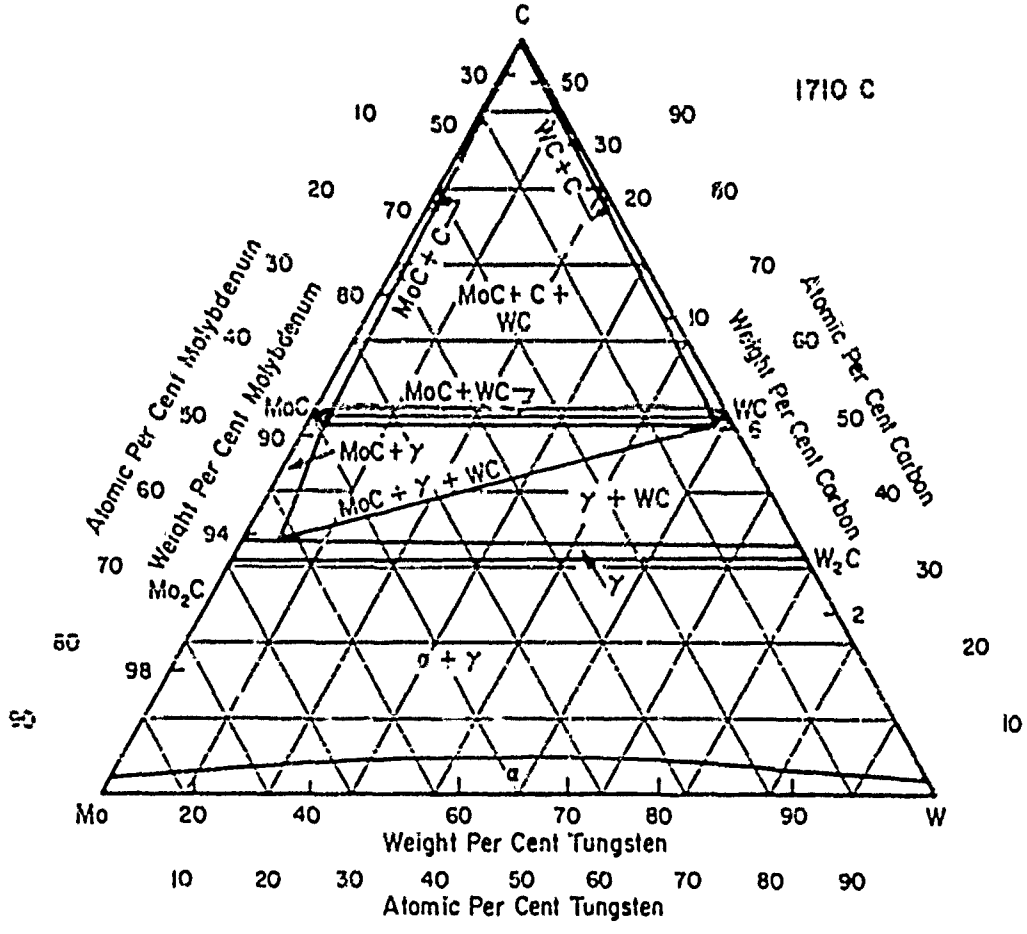
MOLYBDENUM-TANTALUM-VANADIUM SYSTEM[206]



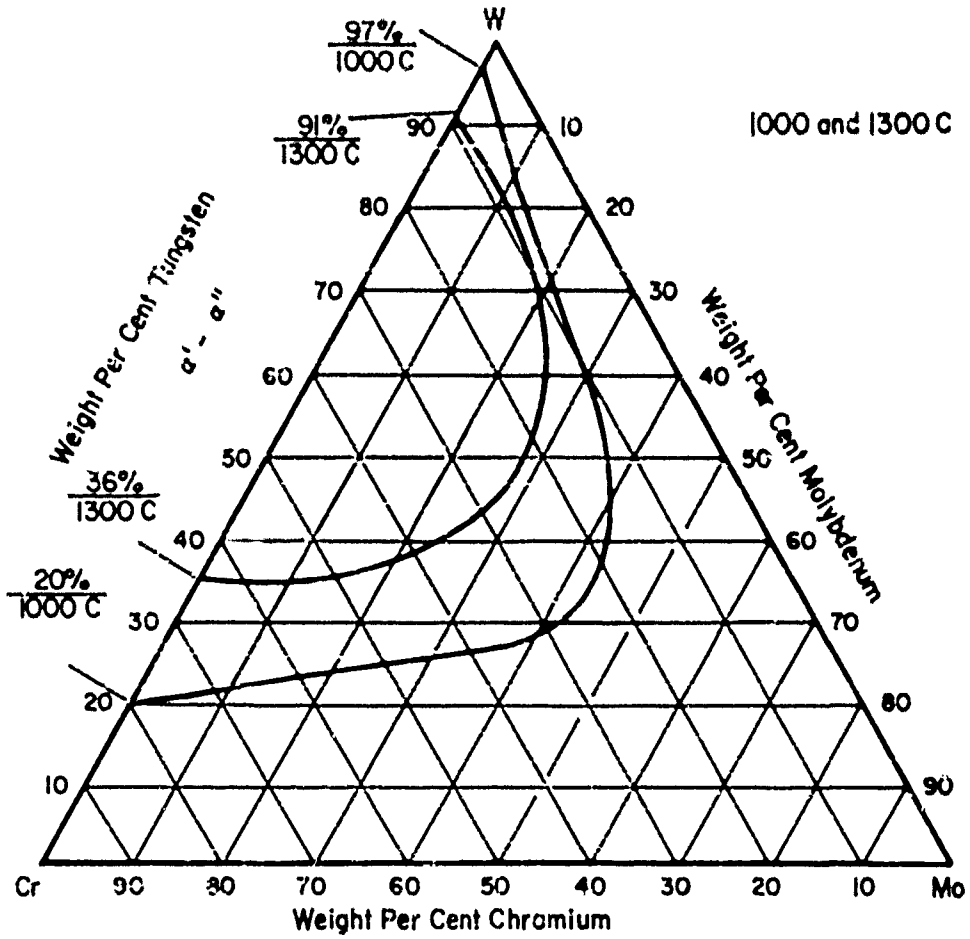
MOLYBDENUM-TANTALUM-TUNGSTEN SYSTEM[206]



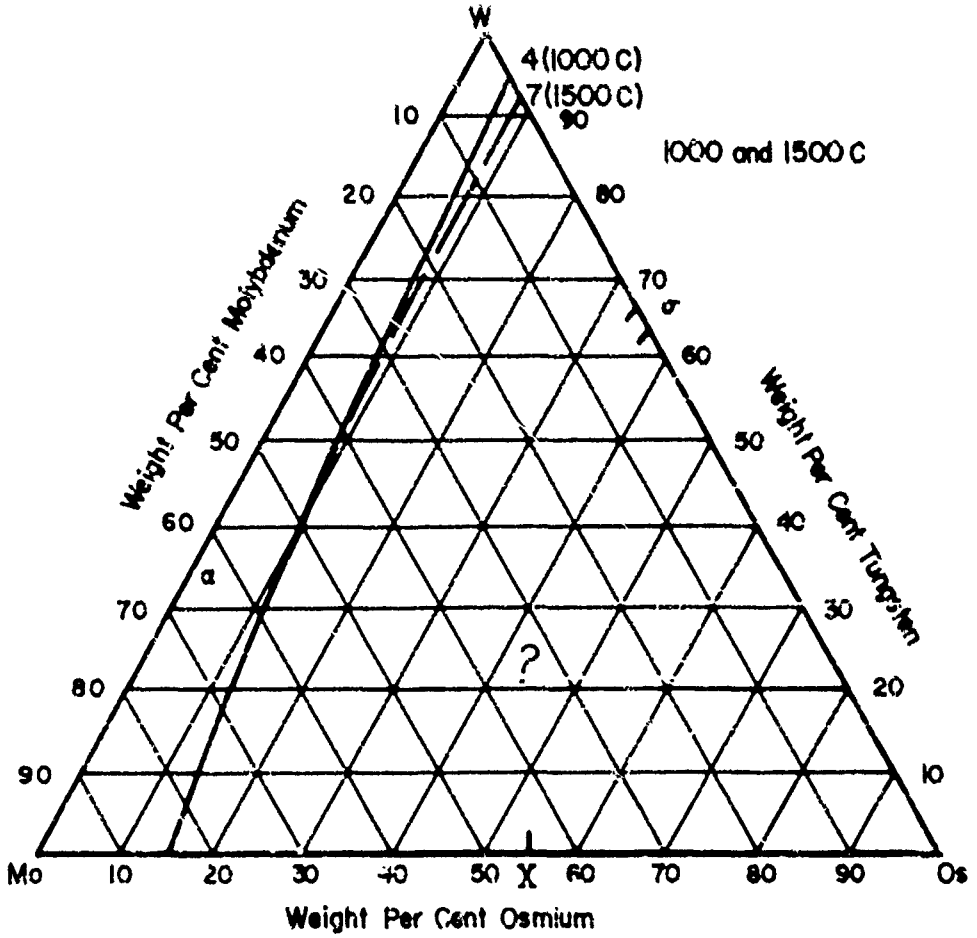
MOLYBDENUM-TUNGSTEN-CARBON SYSTEM[215]

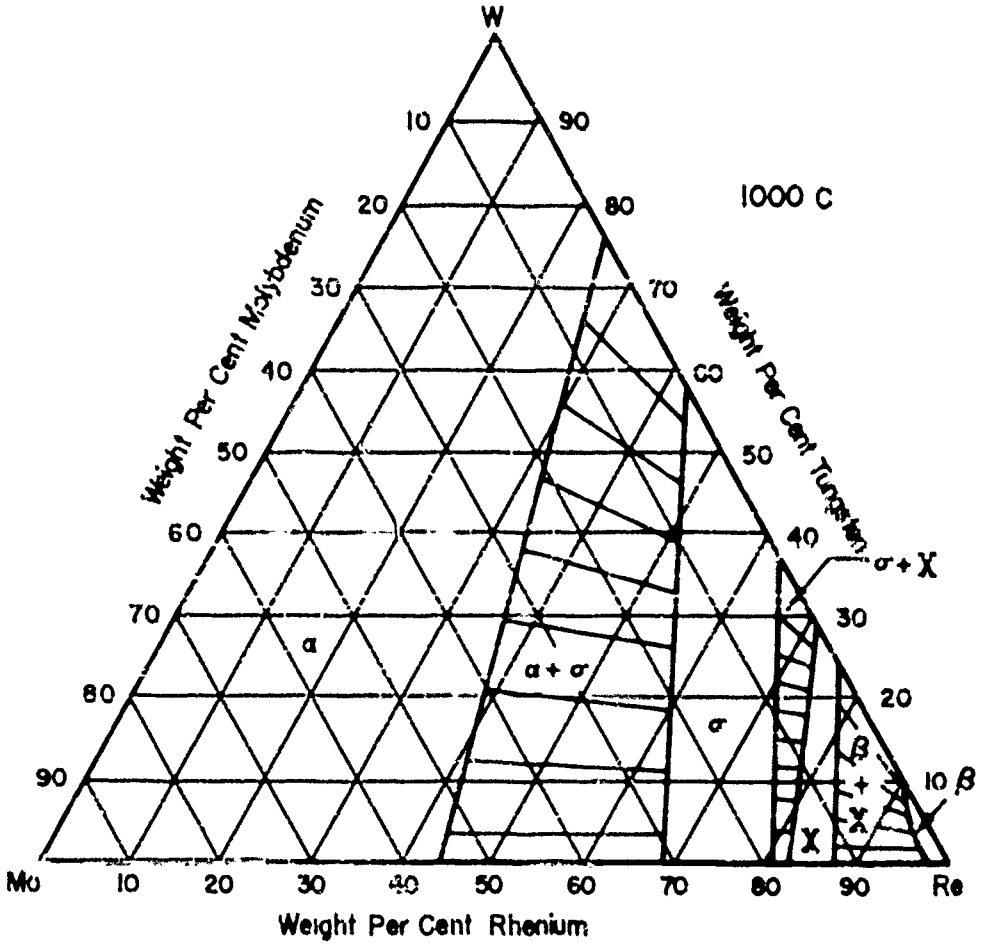


MOLYBDENUM-TUNGSTEN-CHROMIUM SYSTEM(218)

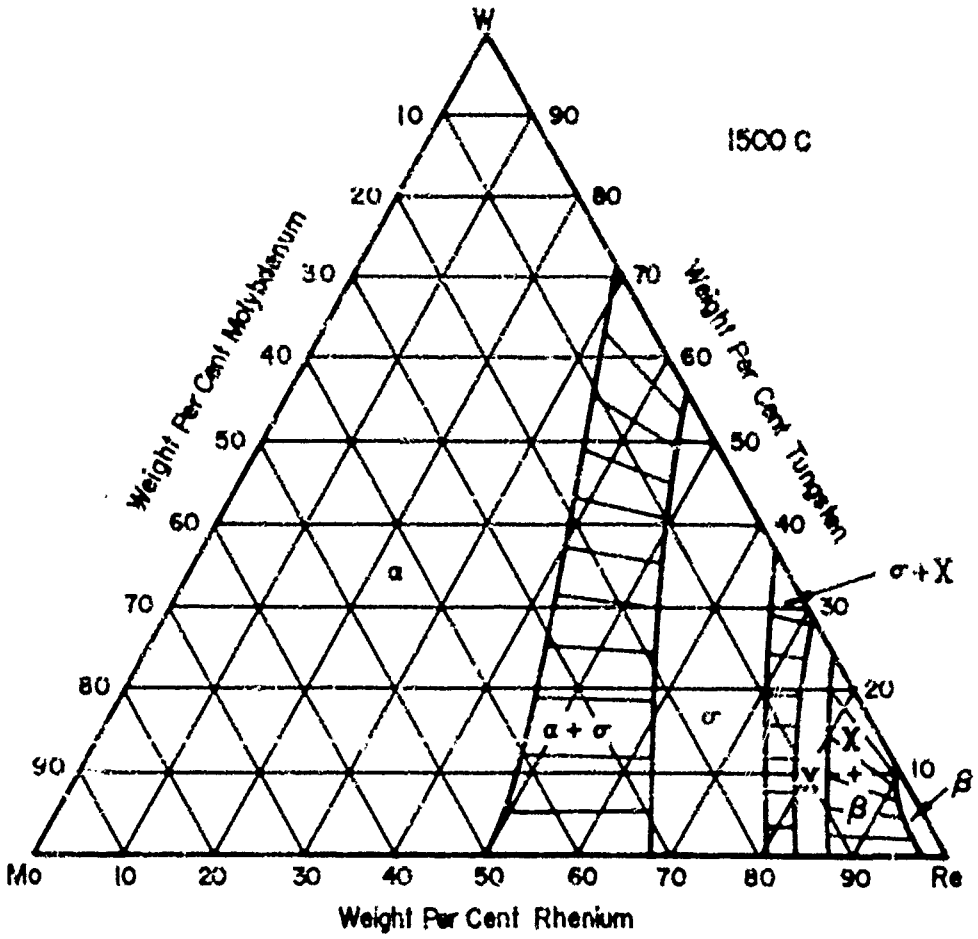


MOLYBDENUM-TUNGSTEN-OSMIUM SYSTEM[206]

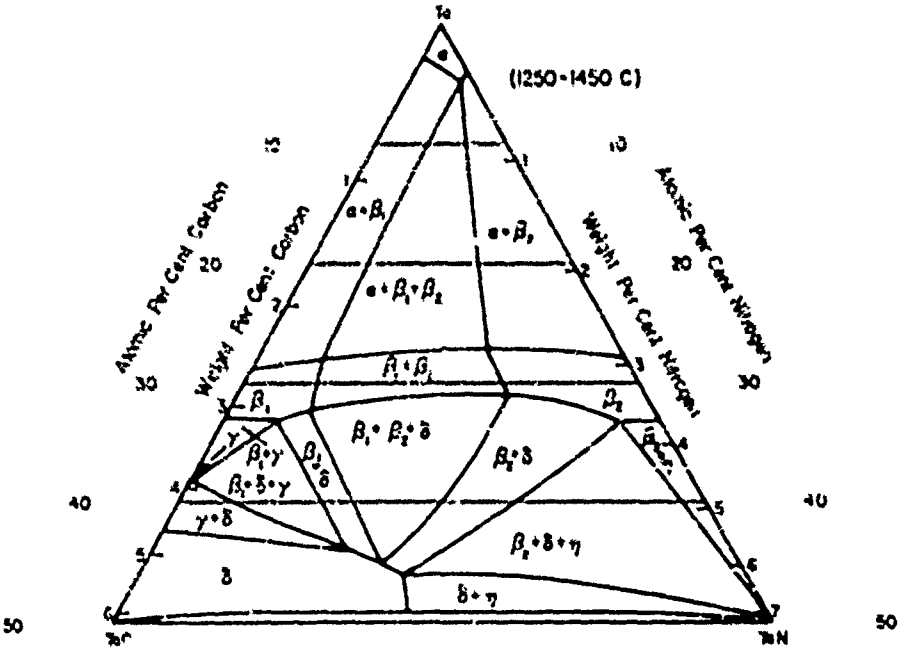



W
10
90
20
80
30
70
40
60
50
50
60
40
70
30
80
20
90
10
Mo
10
20
30
40
50
60
70
80
90
Re
1000 C
Weight Per Cent Molybdenum
Weight Per Cent Tungsten
Weight Per Cent Rhenium
α
α + σ
σ
σ + X
β + X
X
β

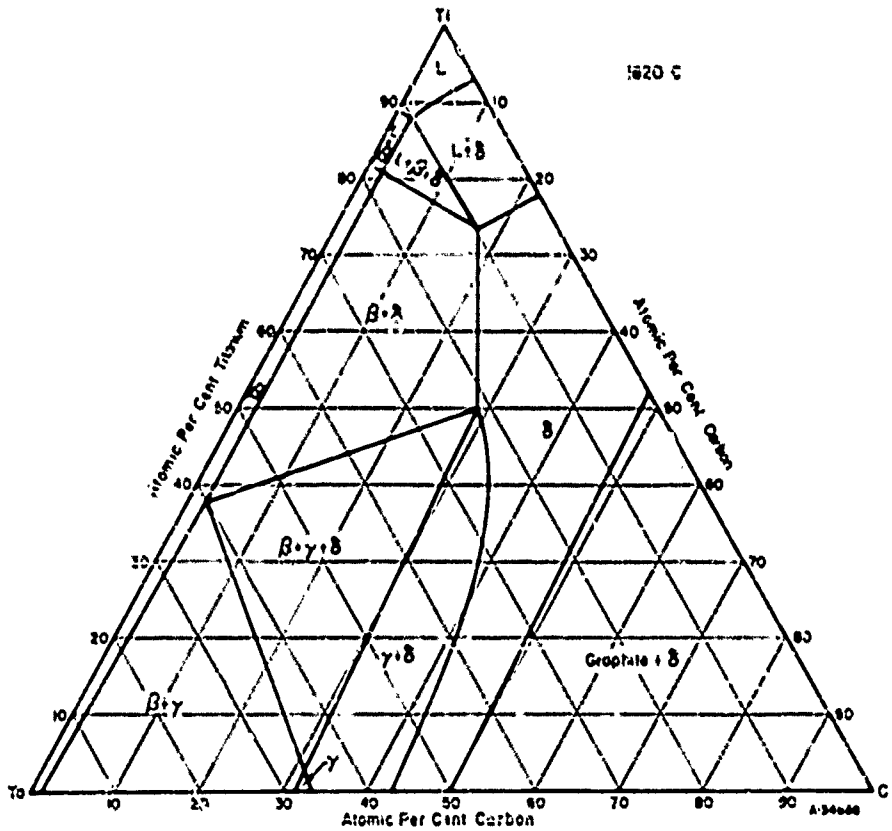
MOLYBDENUM-TUNGSTEN-RHENIUM SYSTEM[206]



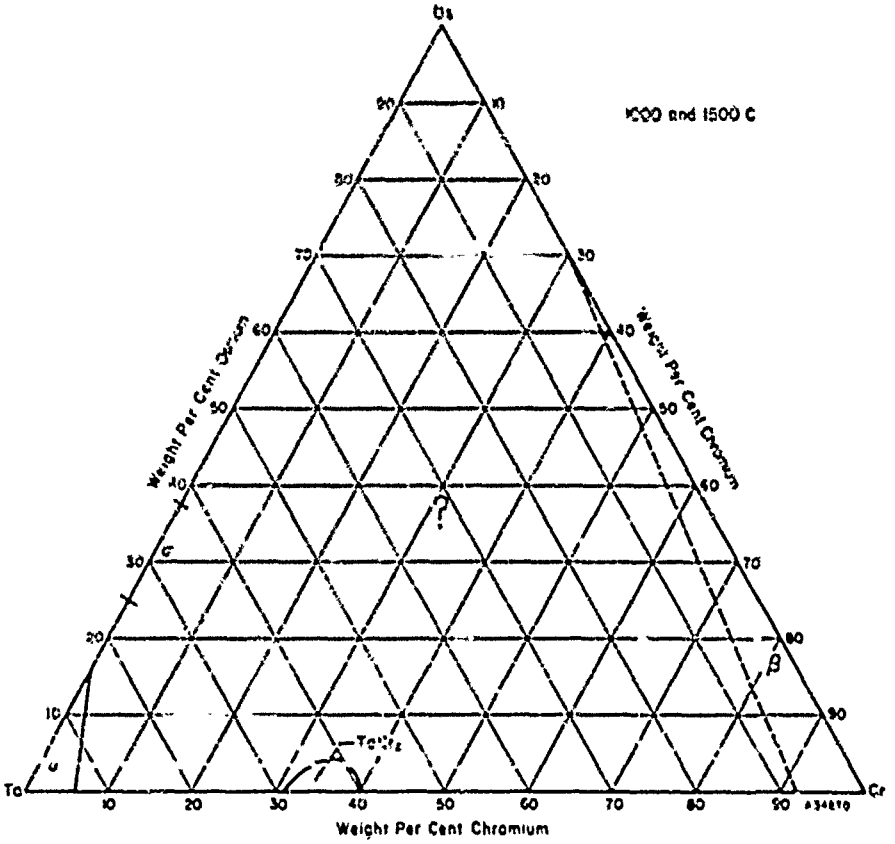
TANTALUM-TANTALUM CARBIDE-TANTALUM NITRIDE SYSTEM[219]



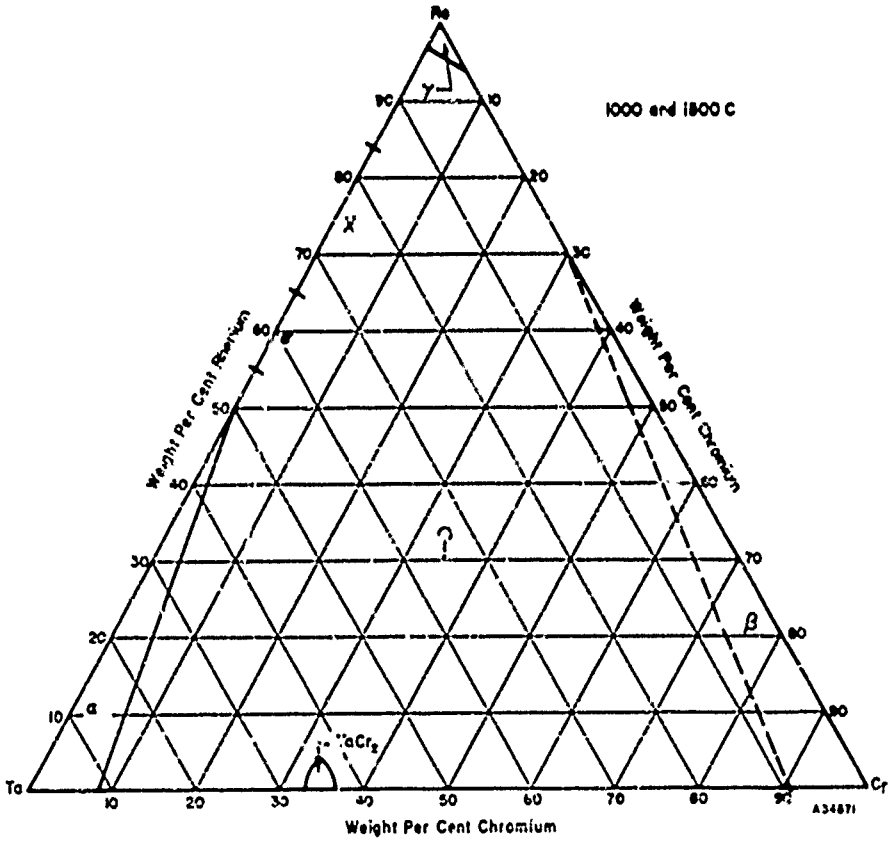
TANTALUM-CARBON-TITANIUM SYSTEM(220)

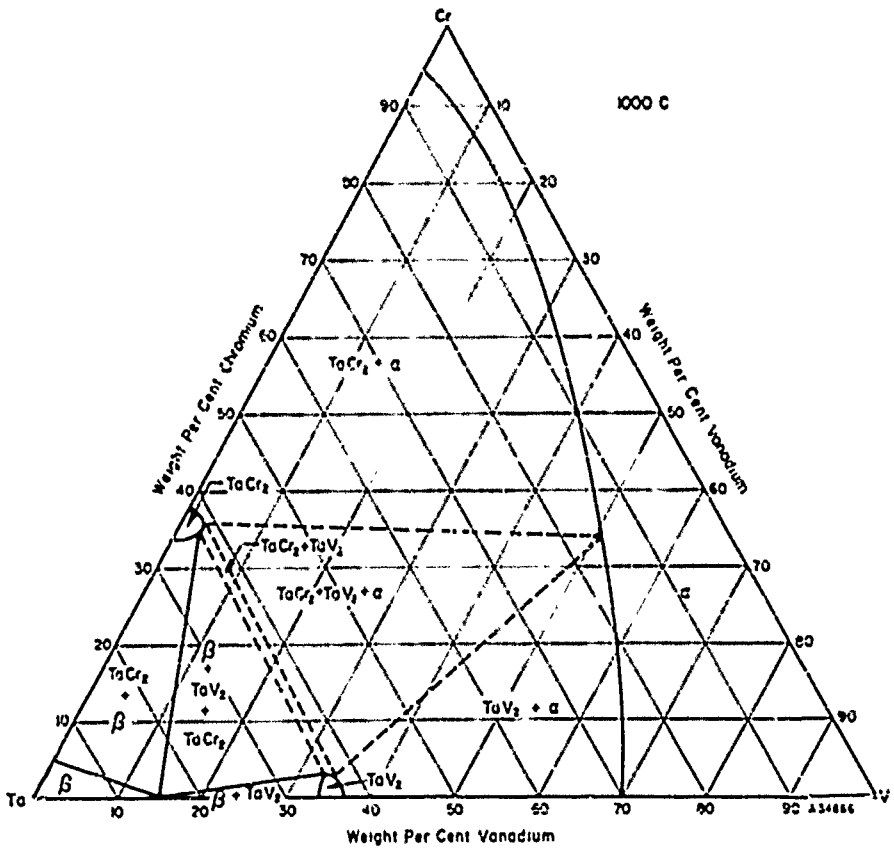


TANTALUM-CHROMIUM-OSMIUM SYSTEM[206]

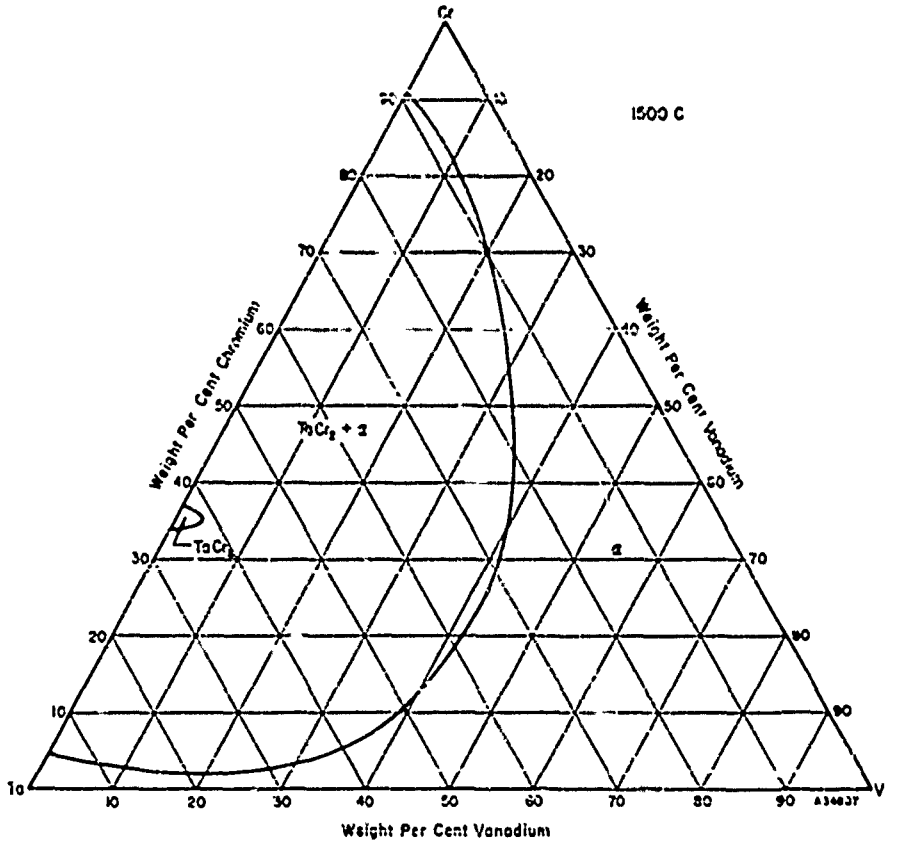


TANTALUM-CHROMIUM-RHENIUM SYSTEM(206)

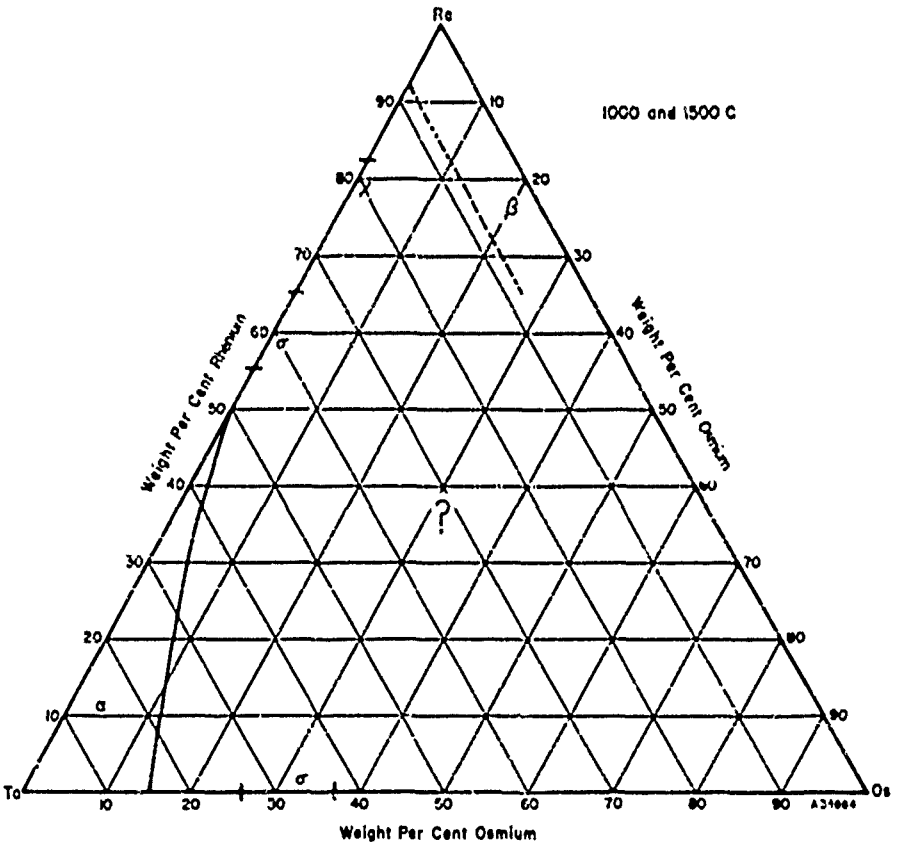



Cr
1000 C
Weight Per Cent Chromium
Weight Per Cent Vanadium
Weight Per Cent Vanadium
Ta
V
TaCr2 + α
TaCr2
TaCr2+TaV2
TaCr2+TaV2+α
β
TaCr2
+
TaV2
+
TaCr2
β
β
TaV2 + α
α
β + TaV2
TaV2

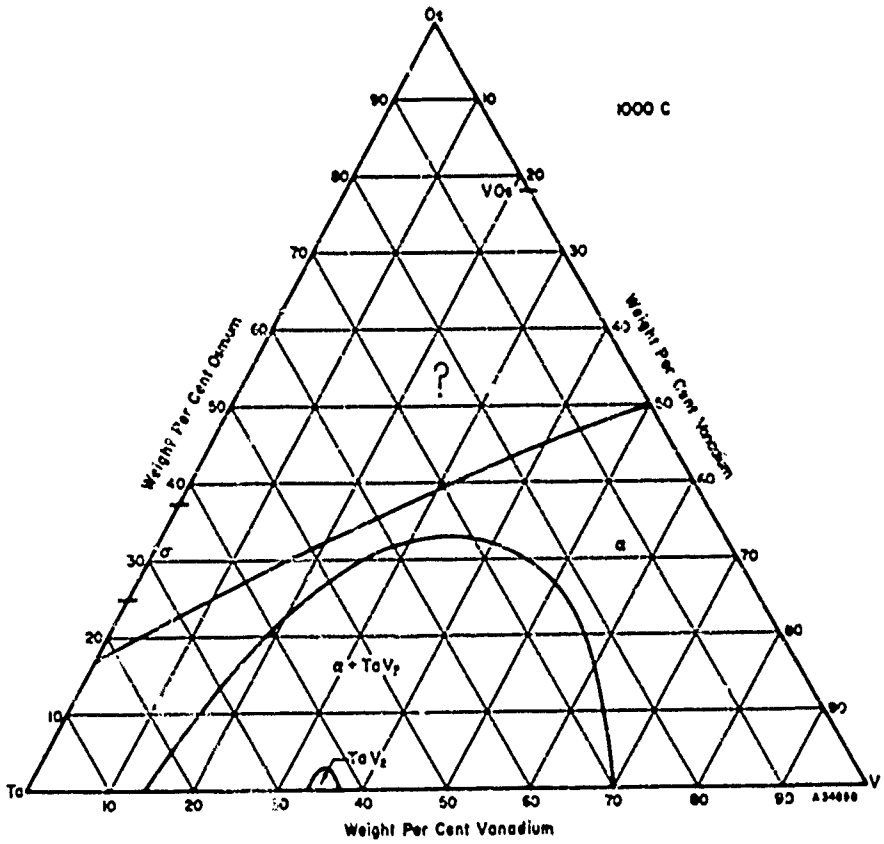
TANTALUM-CHROMIUM-VANADIUM SYSTEM(206)



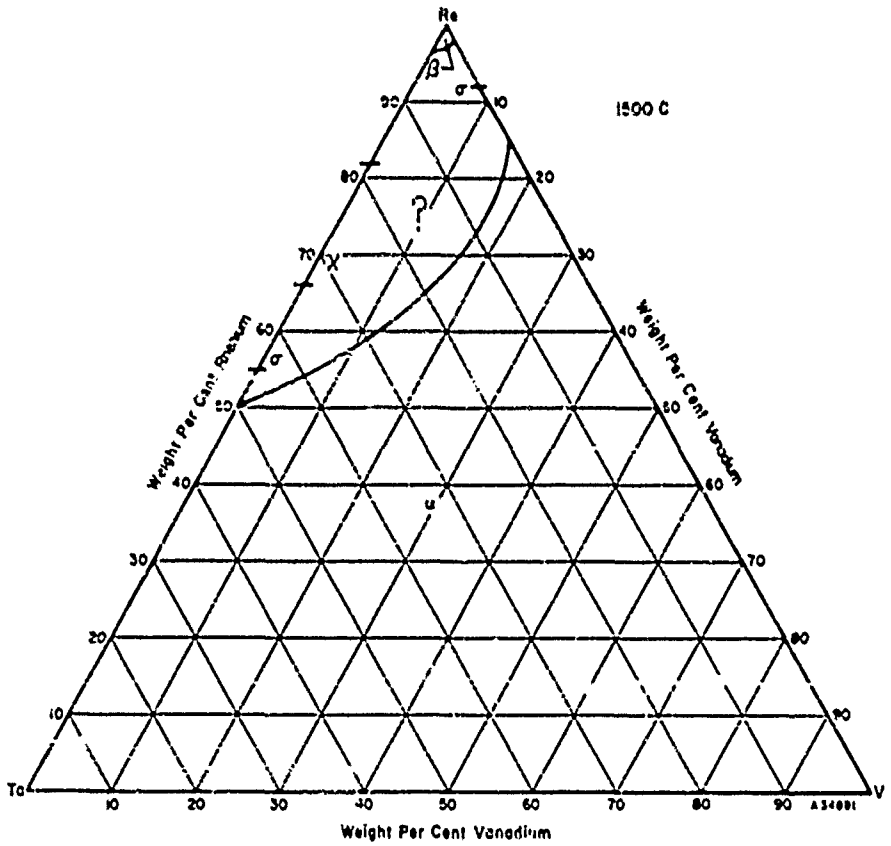
TANTALUM-OSMIUM-RHENIUM SYSTEM(206)



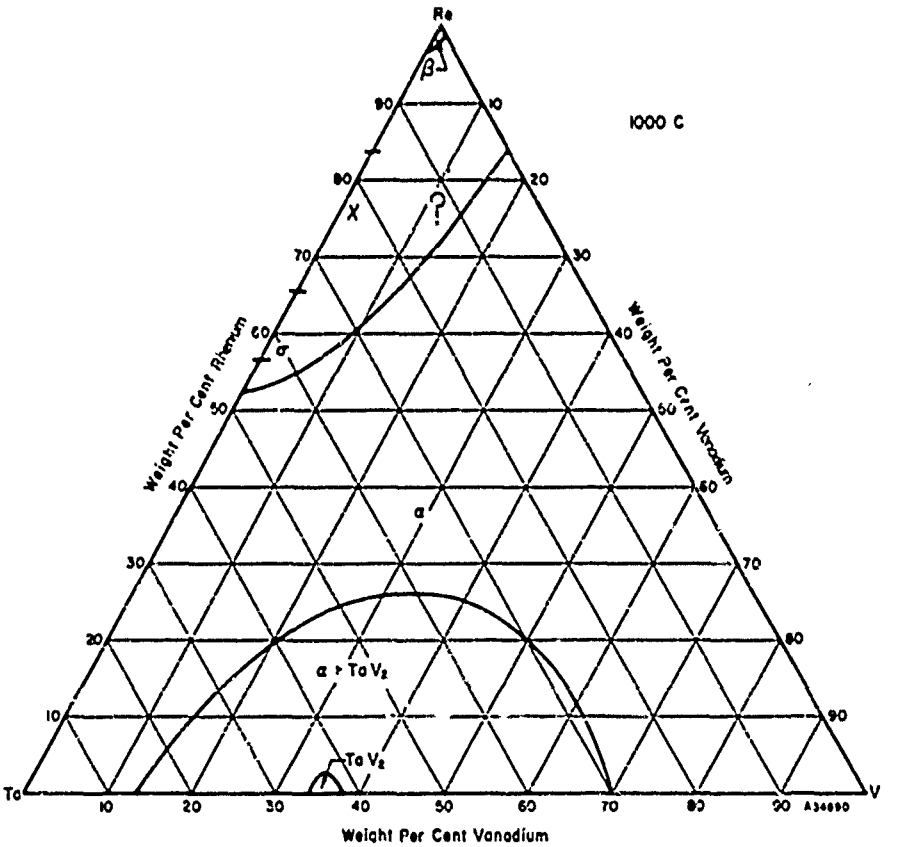
TANTALUM-OSMIUM-VANADIUM SYSTEM(206)



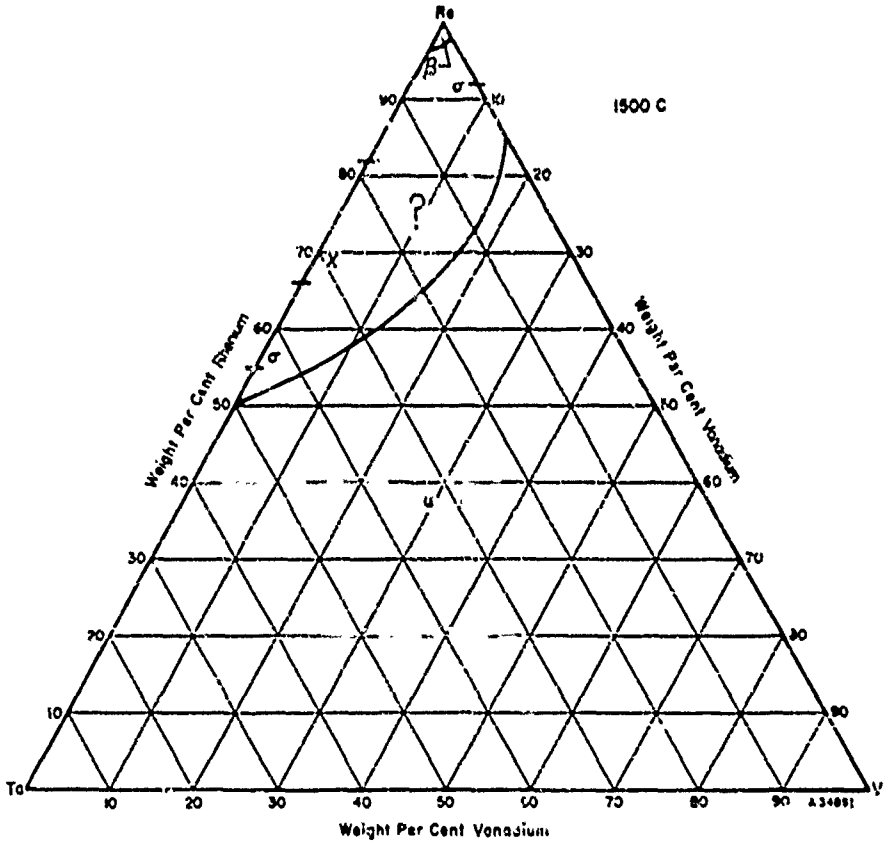
TANTALUM-OSMIUM-VANADIUM SYSTEM(206)



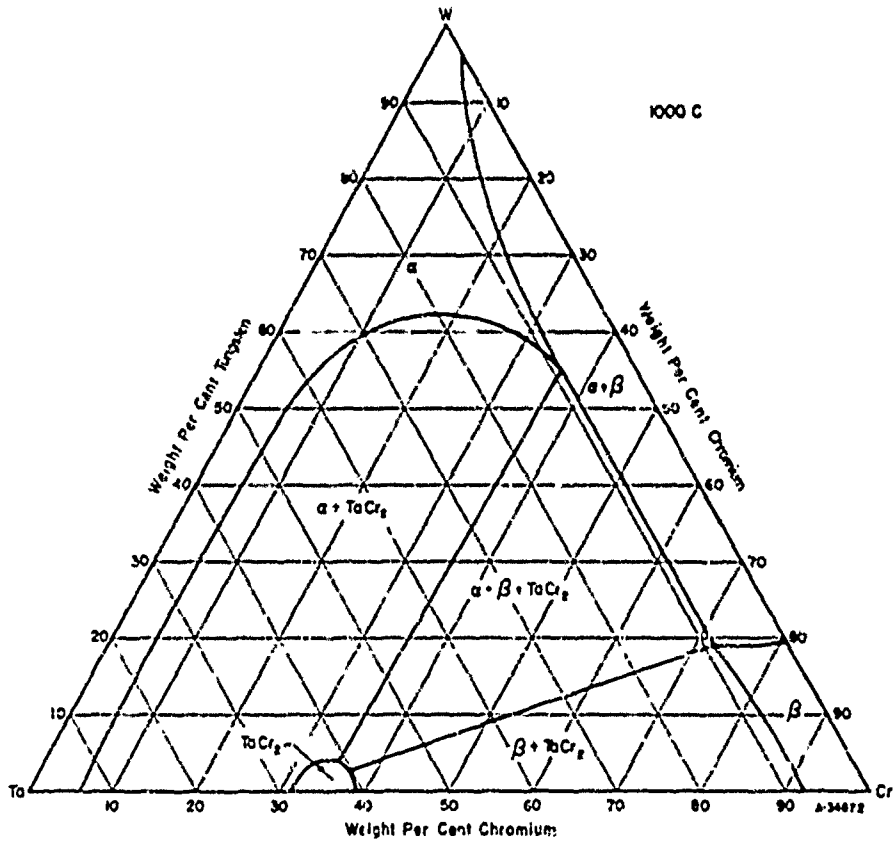
TANTALUM-RHENIUM-VANADIUM SYSTEM(206)



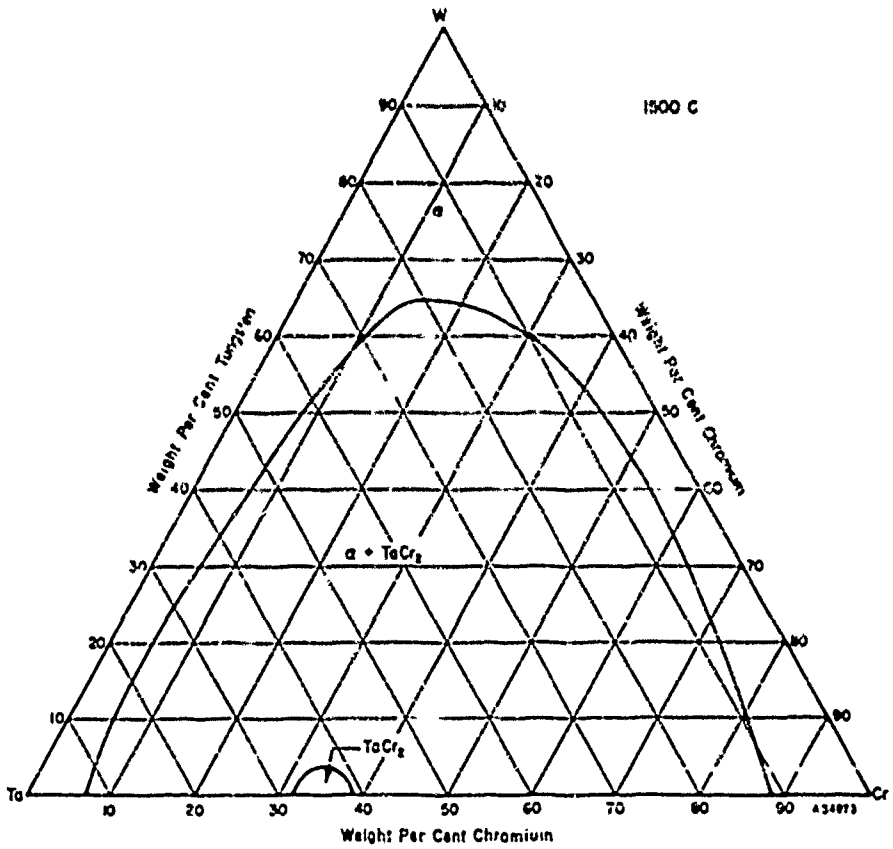
TANTALUM-RHENIUM-VANADIUM SYSTEM(206)



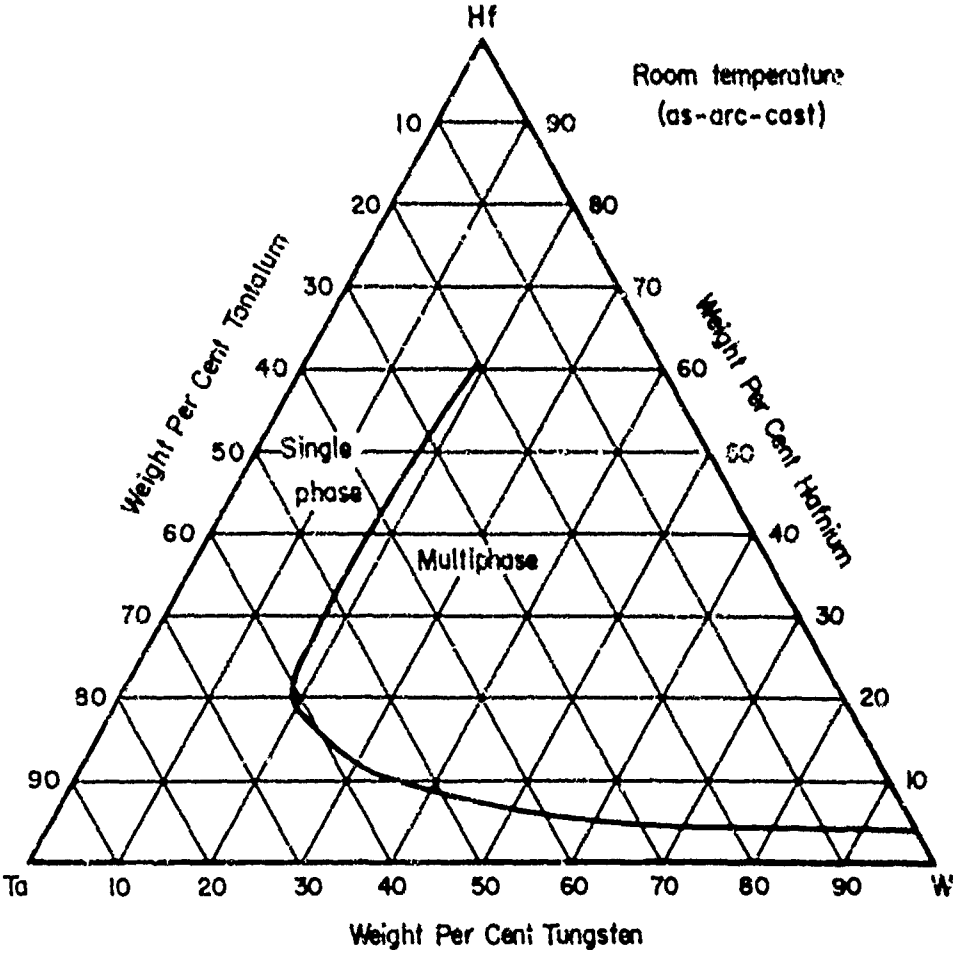
TANTALUM-TUNGSTEN-CHROMIUM SYSTEM[206]



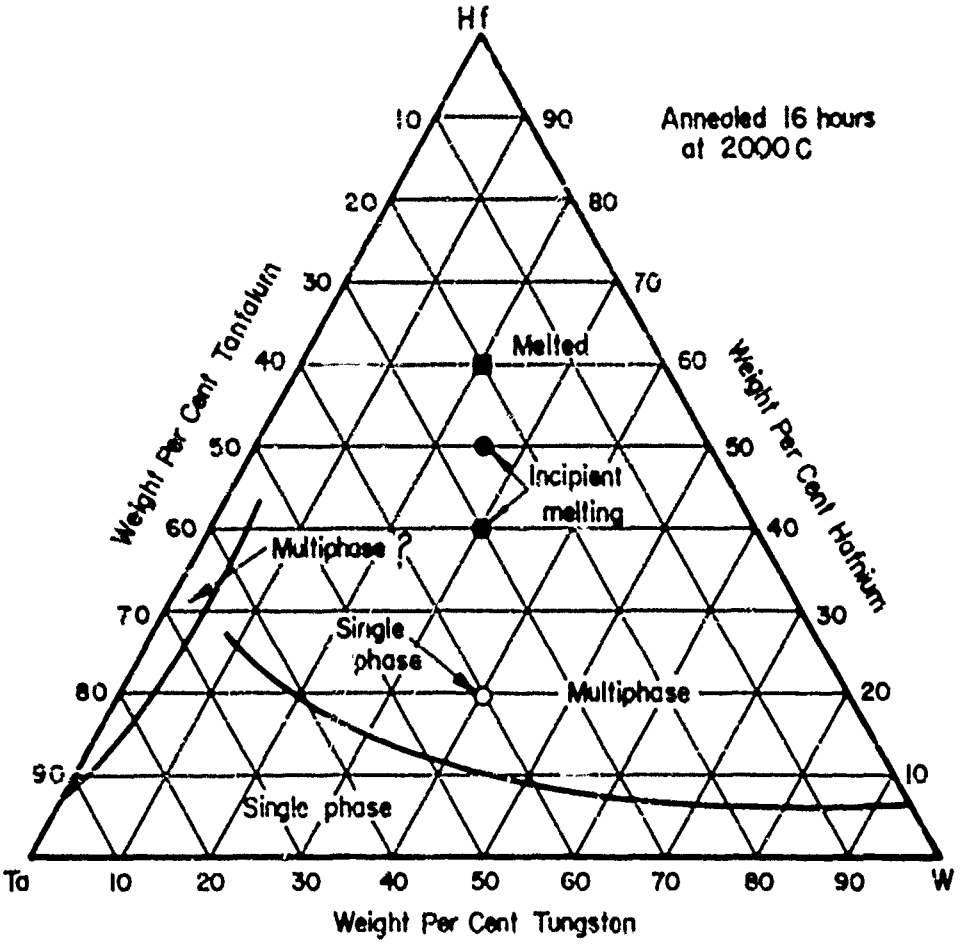
TANTALUM-TUNGSTEN-CHROMIUM SYSTEM(206)



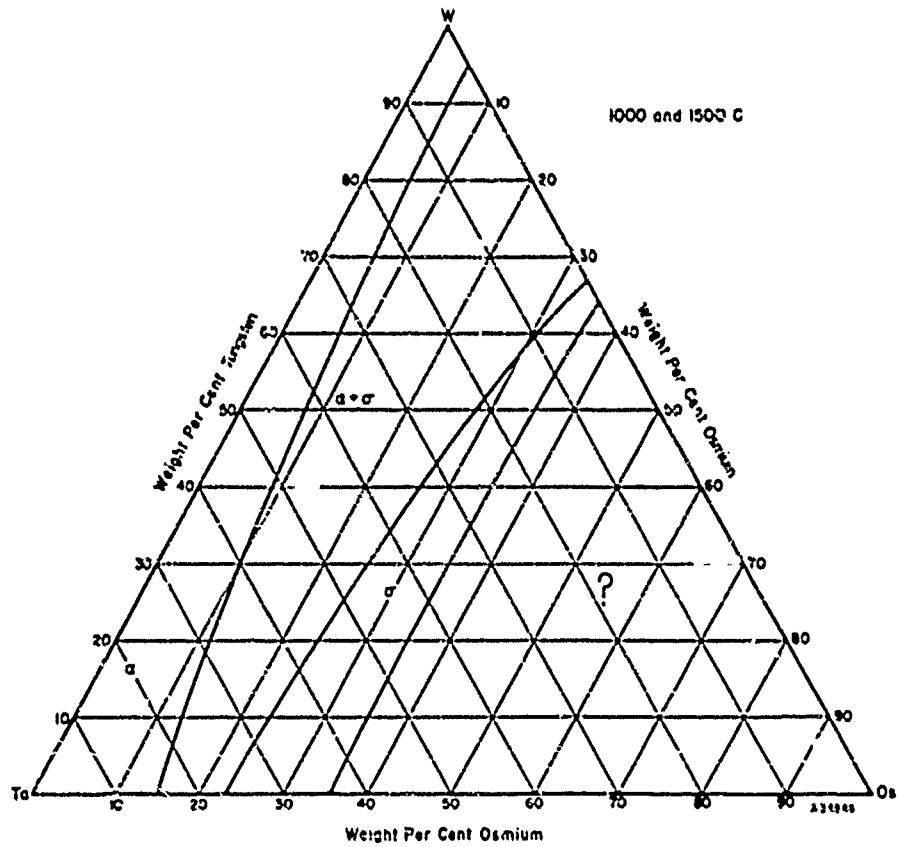
TANTALUM-TUNGSTEN-HAFNIUM SYSTEM[225]

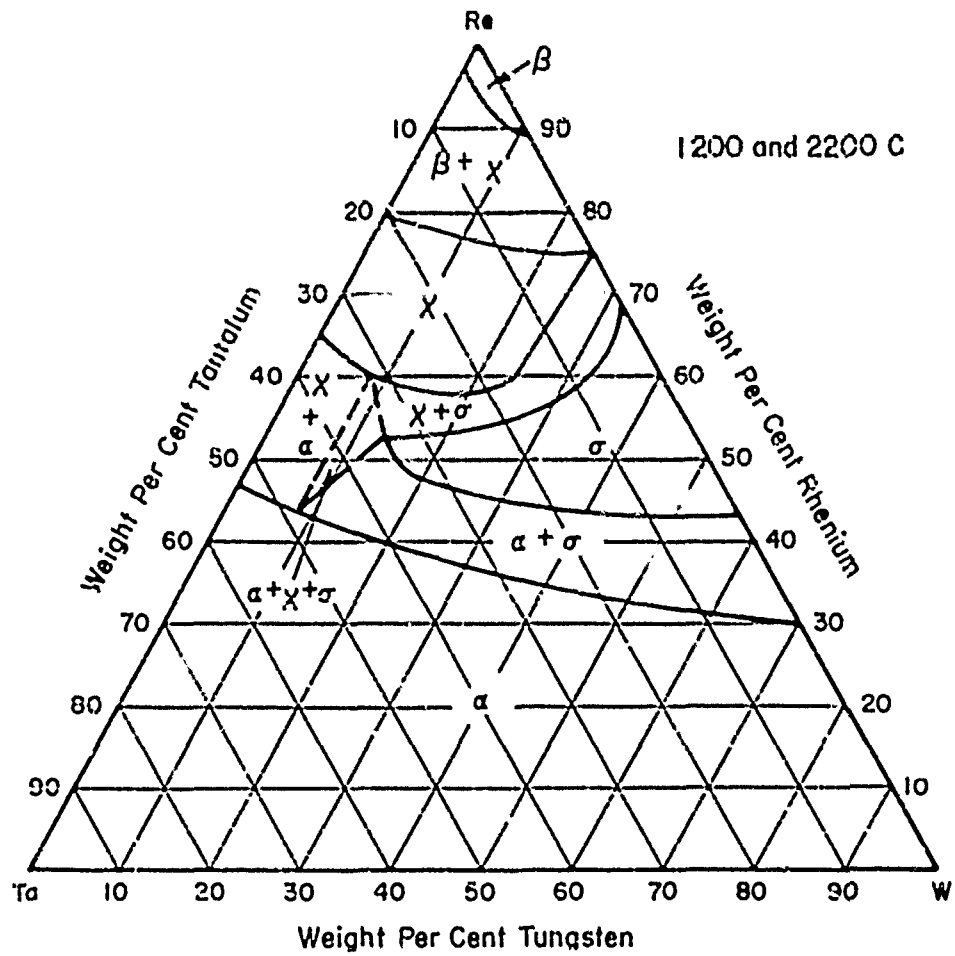


TANTALUM-TUNGSTEN-HAFNIUM SYSTEM(225)

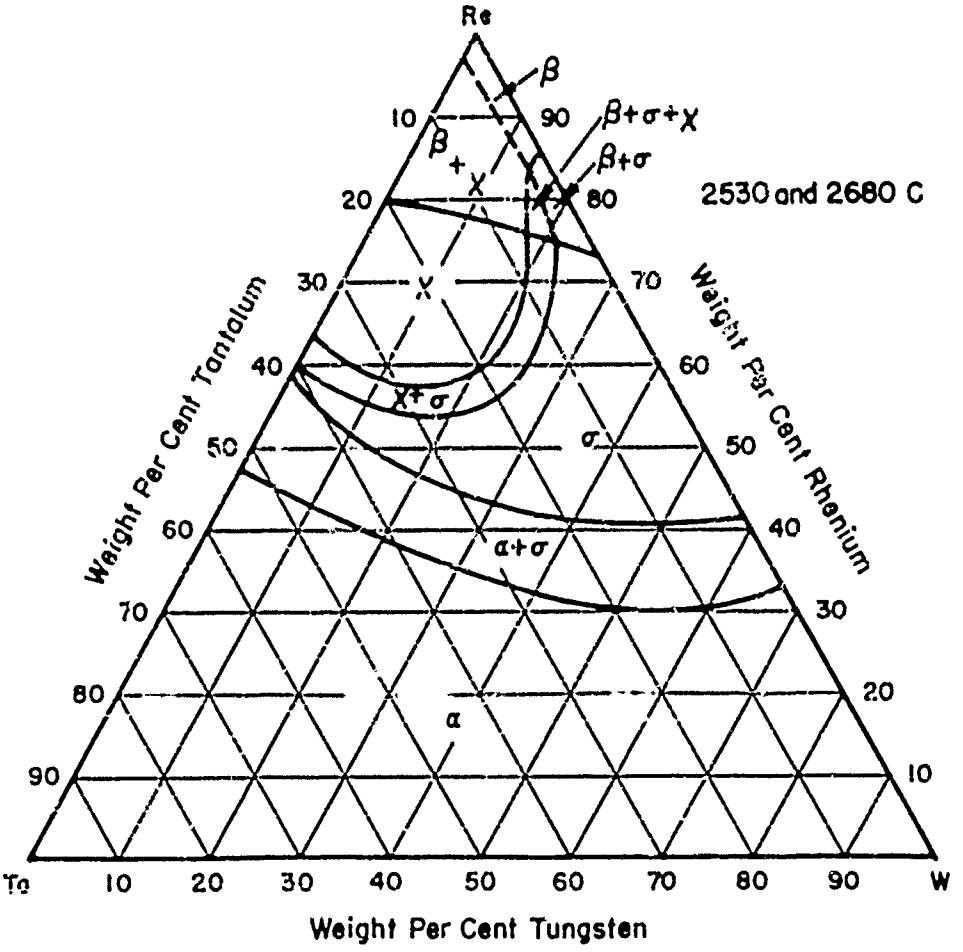


TANTALUM-TUNGSTEN-OSMIUM SYSTEM(206)

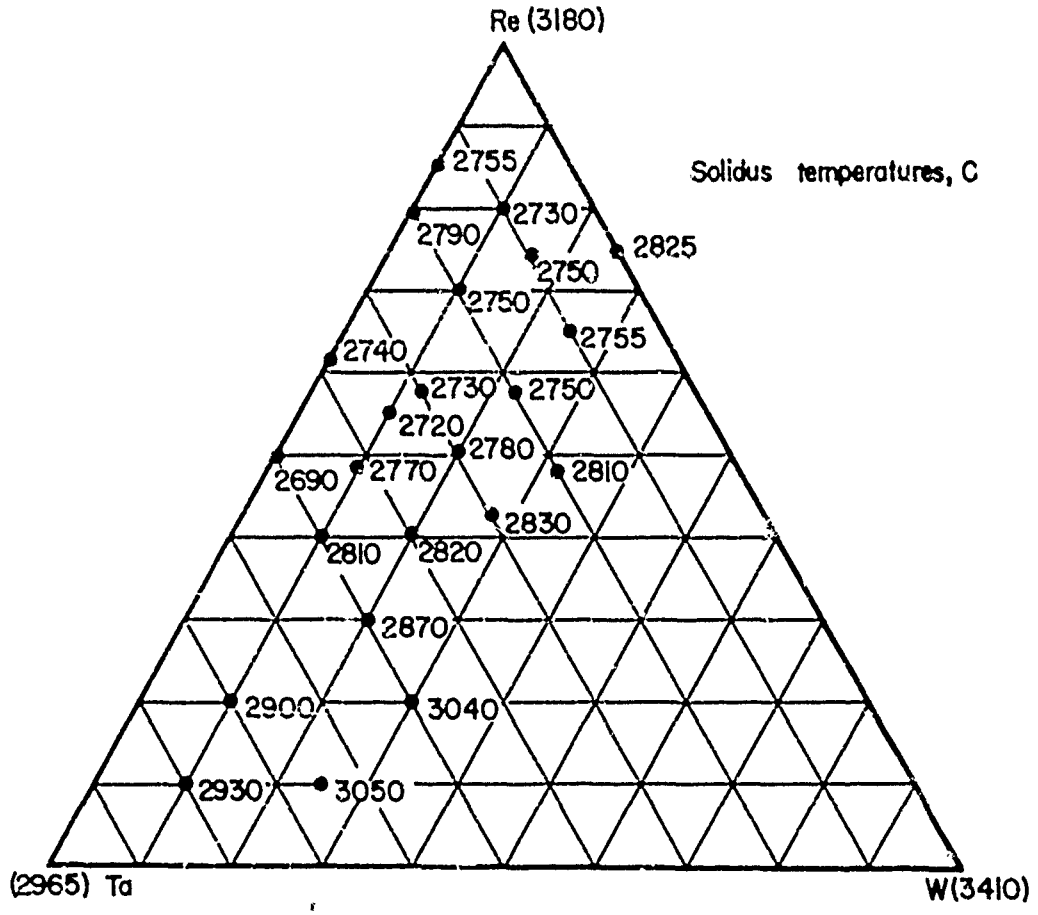


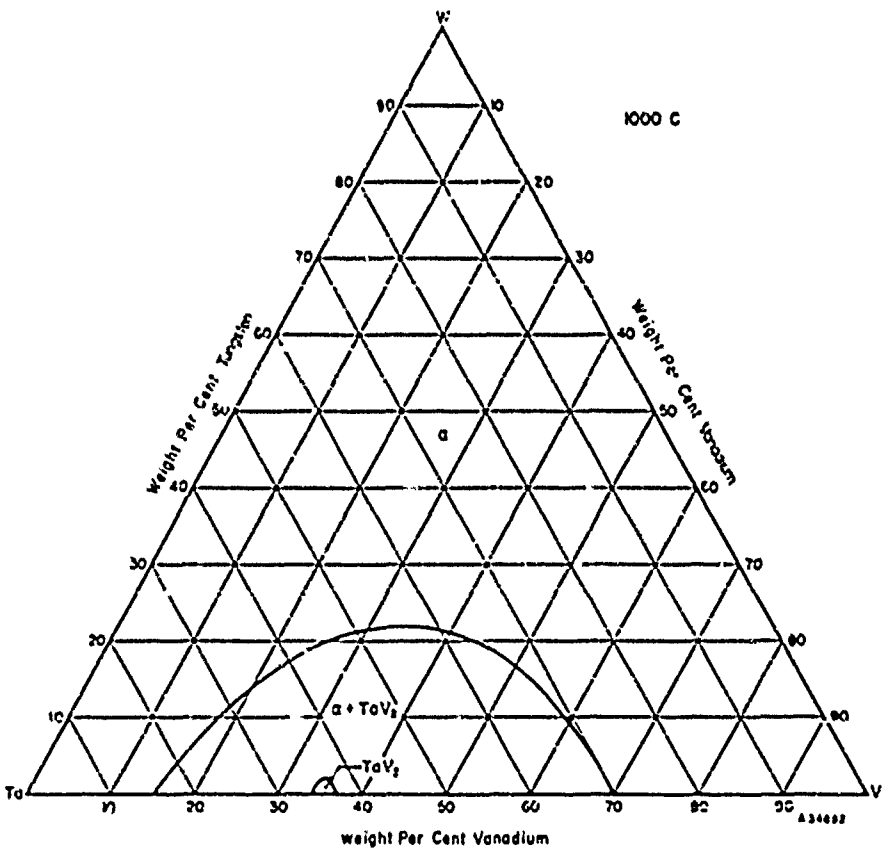

Re
β
10
90
β + χ
1200 and 2200 C
20
80
30
70
χ
40
60
χ
+
χ
χ + σ
α
σ
50
50
60
40
α + σ
α + χ + σ
70
30
80
20
α
90
10
Ta
10
20
30
40
50
60
70
80
90
W
Weight Per Cent Tantalum
Weight Per Cent Rhenium
Weight Per Cent Tungsten

TANTALUM-TUNGSTEN-RHENIUM SYSTEM[149]

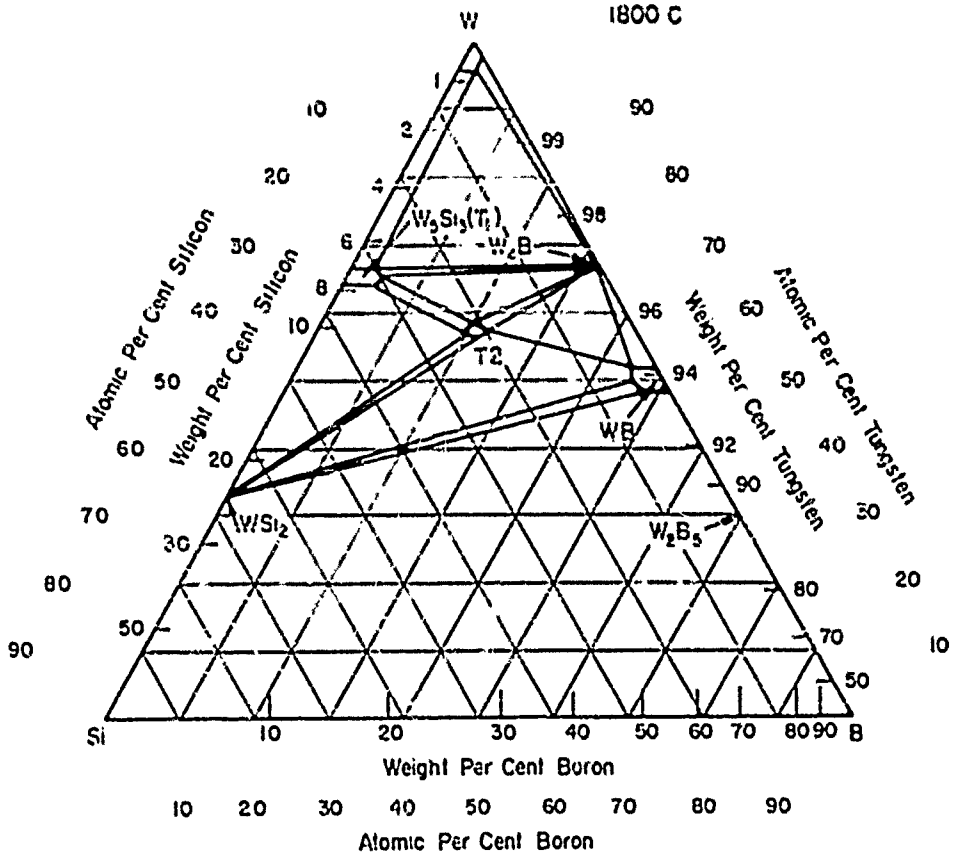


TANTALUM-TUNGSTEN-RHENIUM SYSTEM[149]

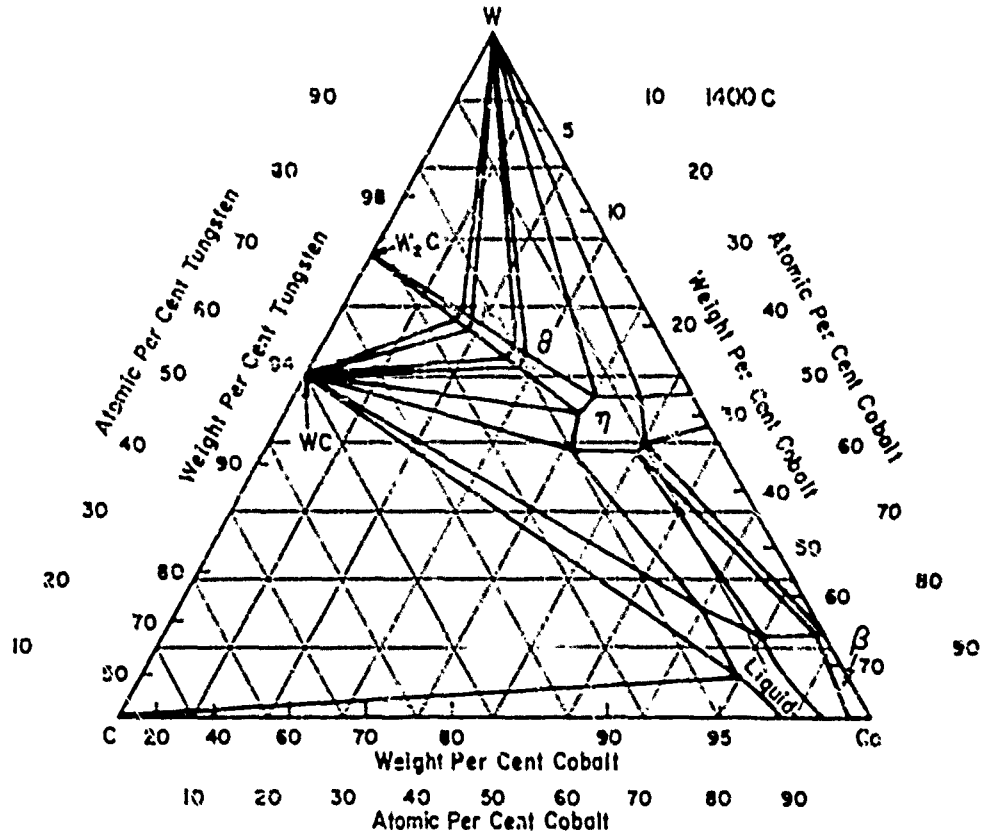



W
1000 C
Weight Per Cent Tungsten
Weight Per Cent Vanadium
α
α + TaV2
TaV2
Ta
V
Weight Per Cent Vanadium

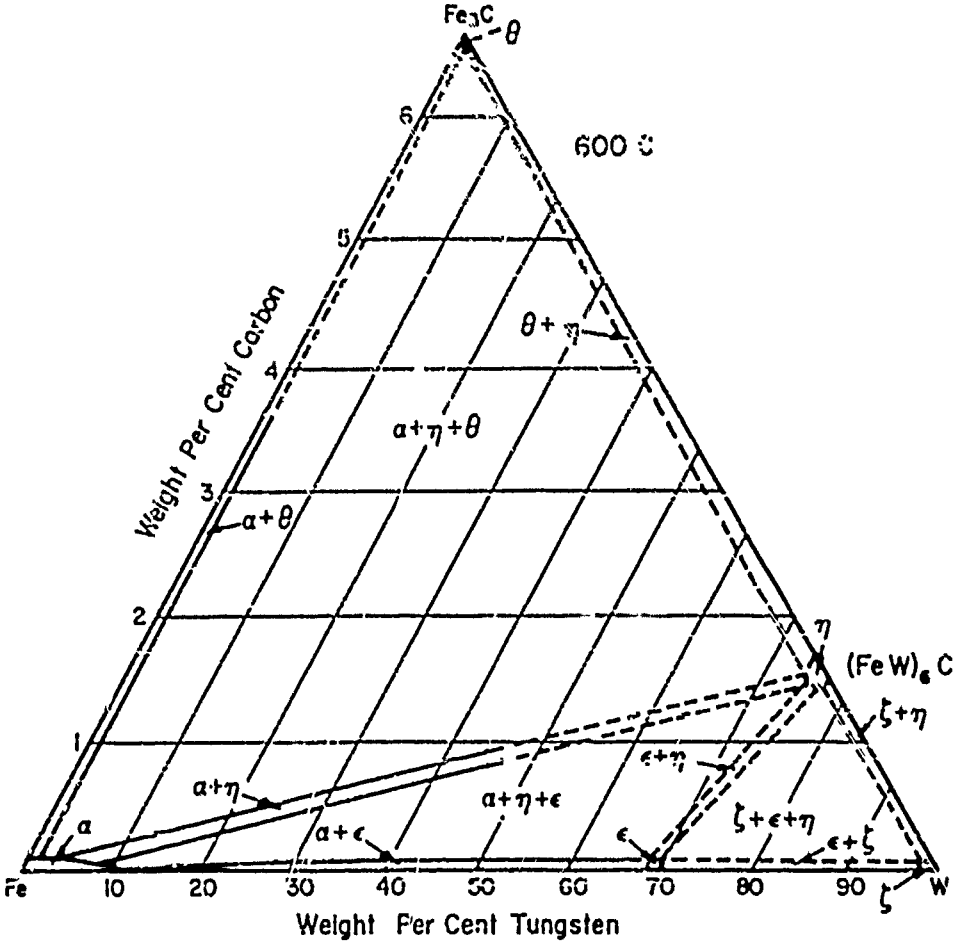
TUNGSTEN-BORON-SILICON SYSTEM(212)



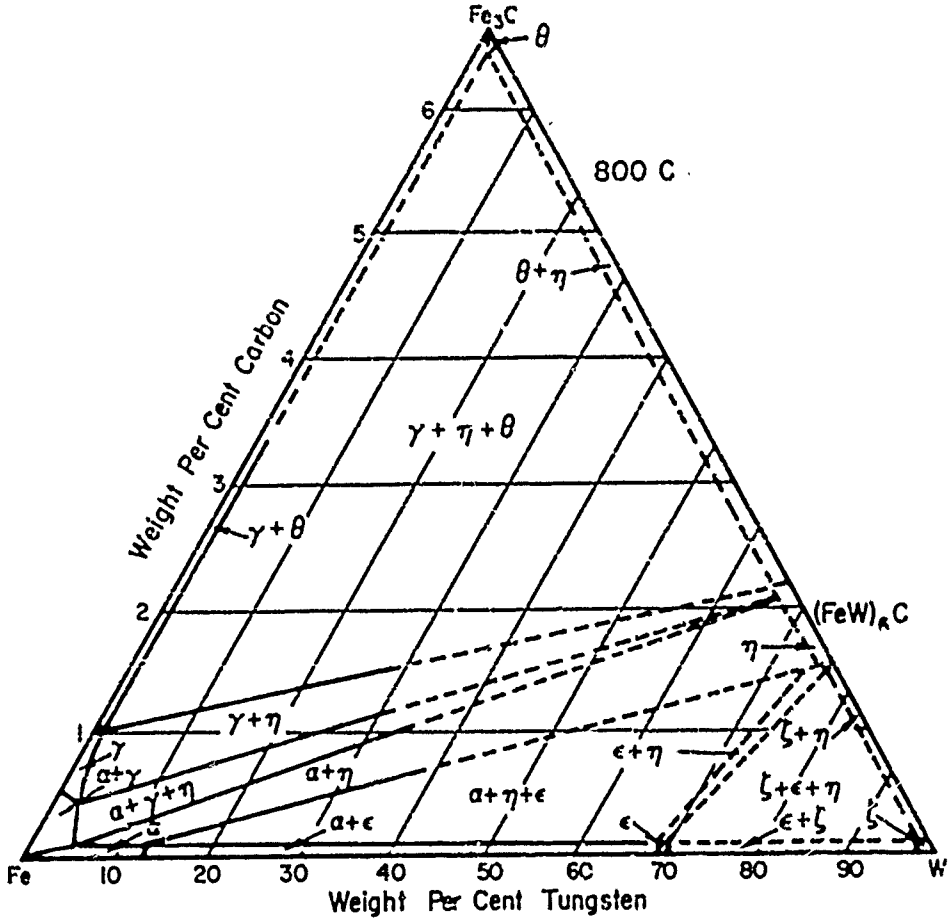
TUNGSTEN-CARBON-COBALT SYSTEM(221)



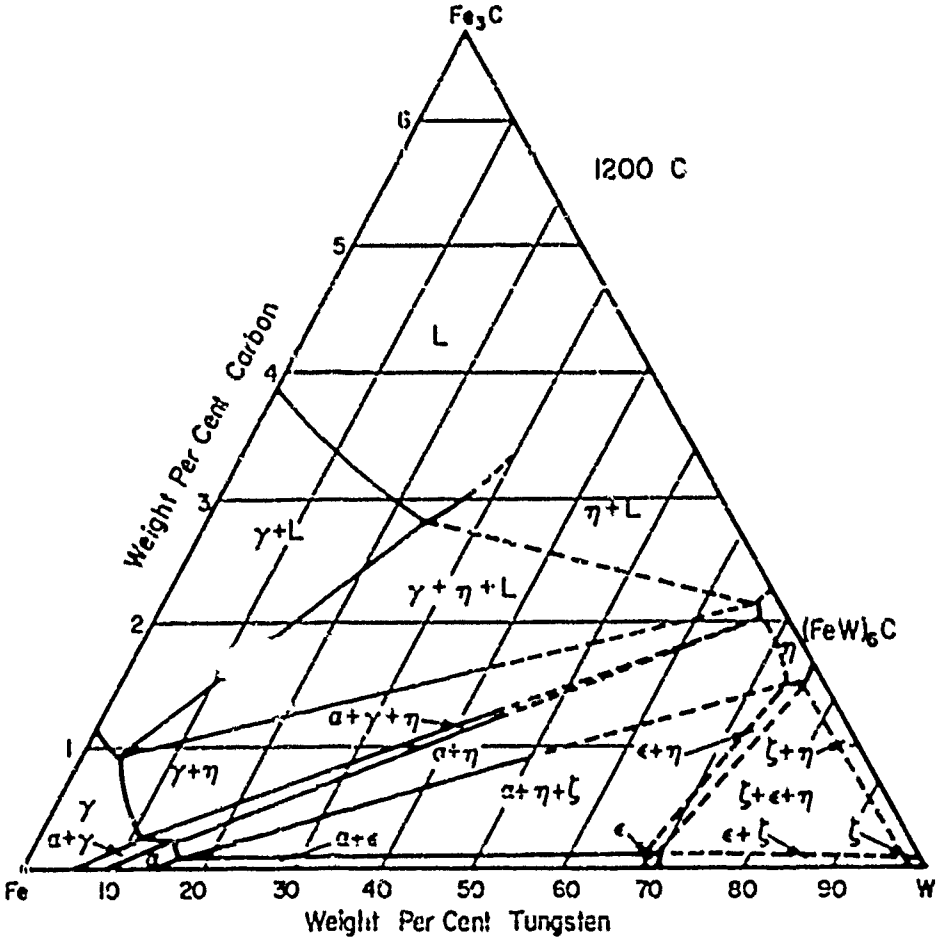
TUNGSTEN-CARBON-IRON SYSTEM(222)



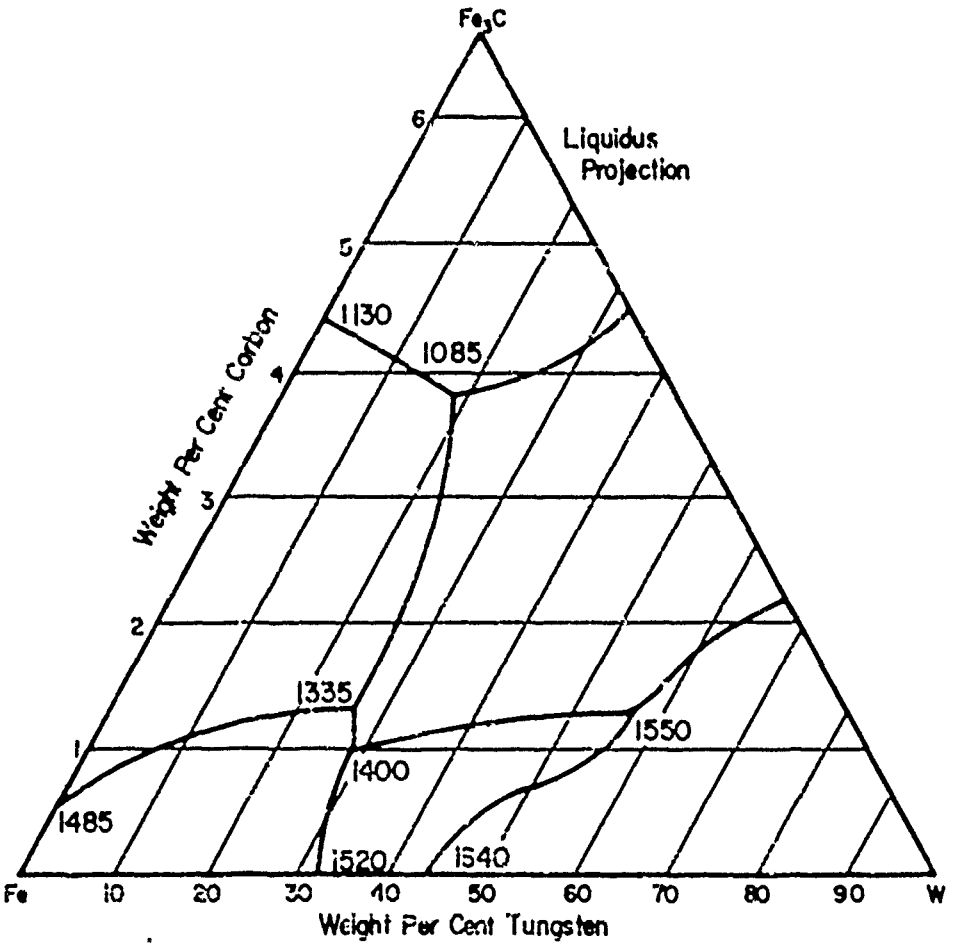
TUNGSTEN-CARBON-IRON SYSTEM(222)



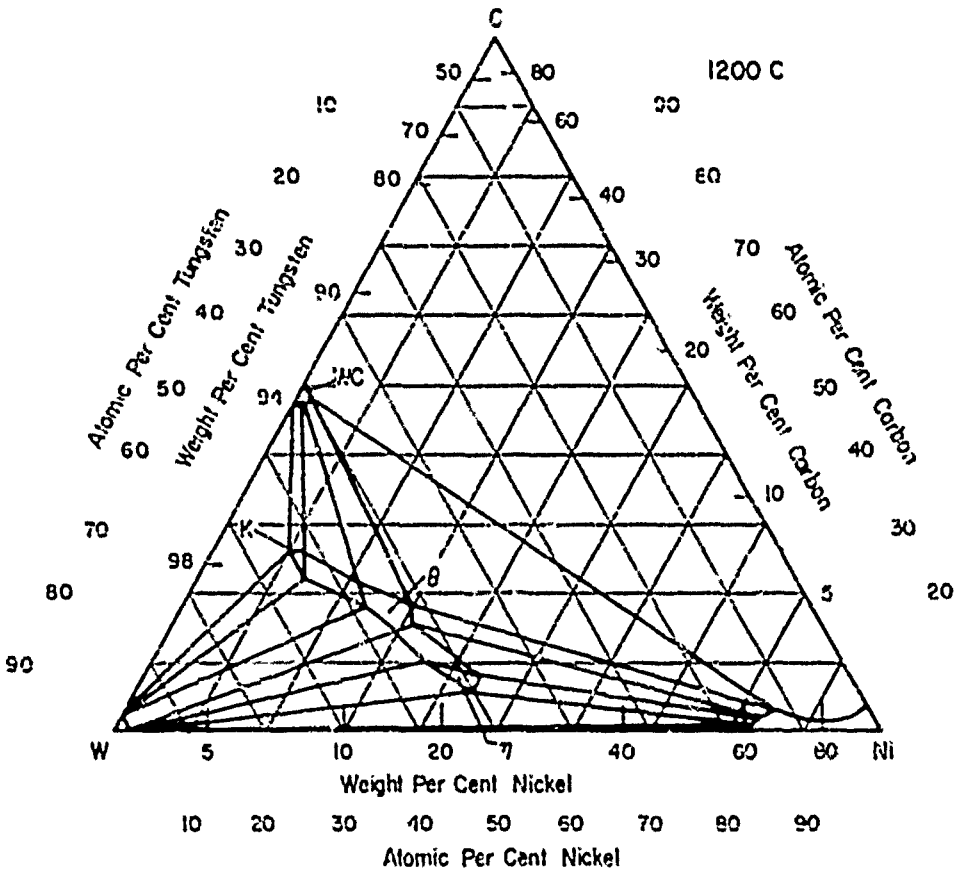
TUNGSTEN-CARBON-IRON SYSTEM(222)



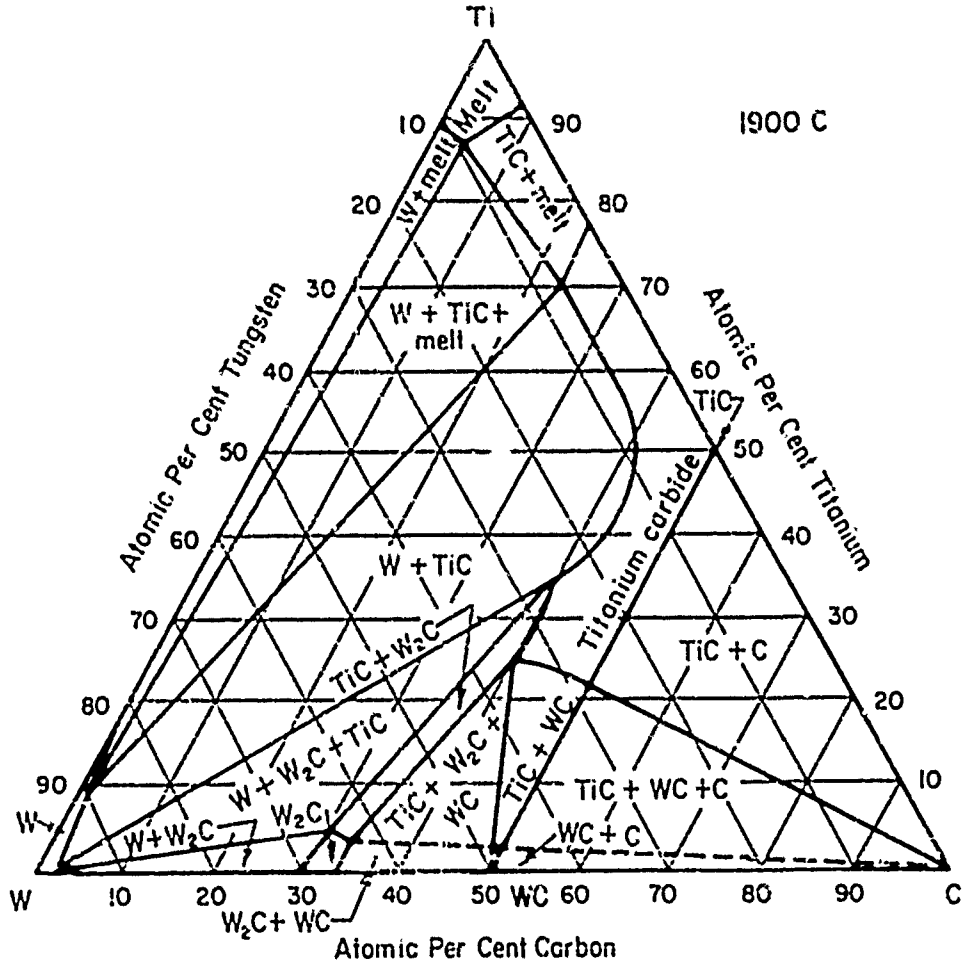
TUNGSTEN-CARBON-IRON SYSTEM[222]

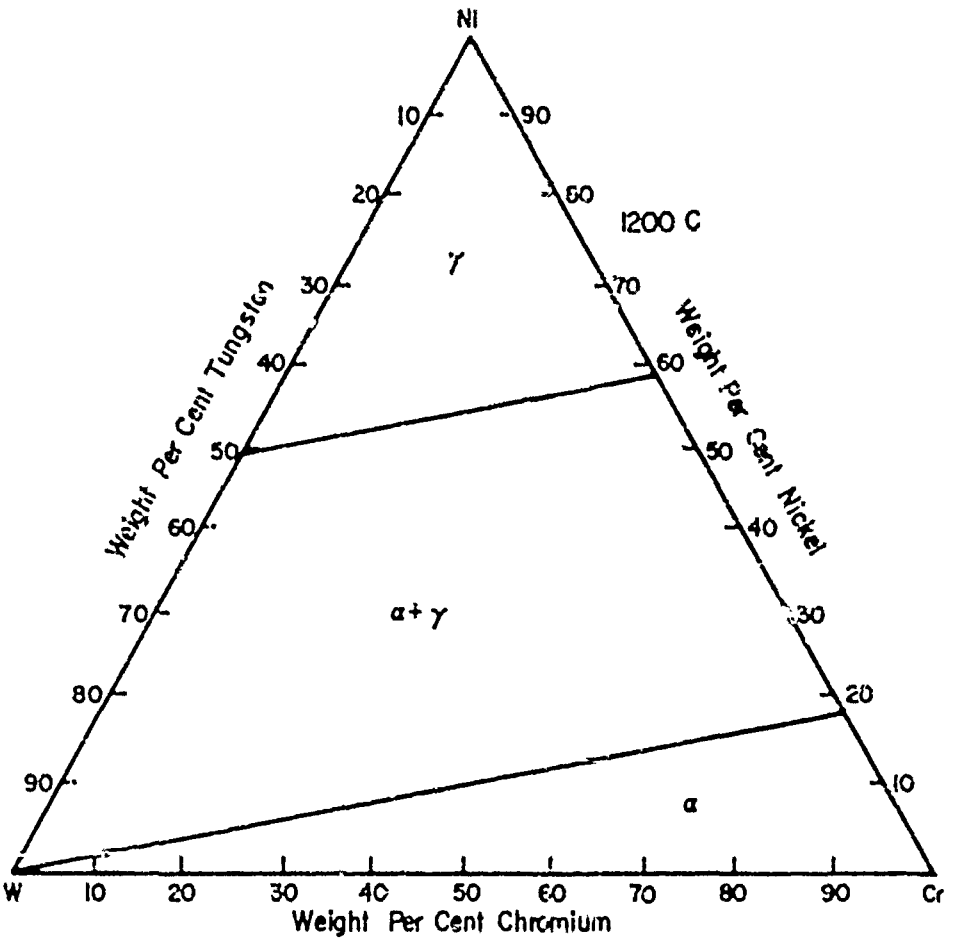


TUNGSTEN-CARBON-NICKEL SYSTEM[223]

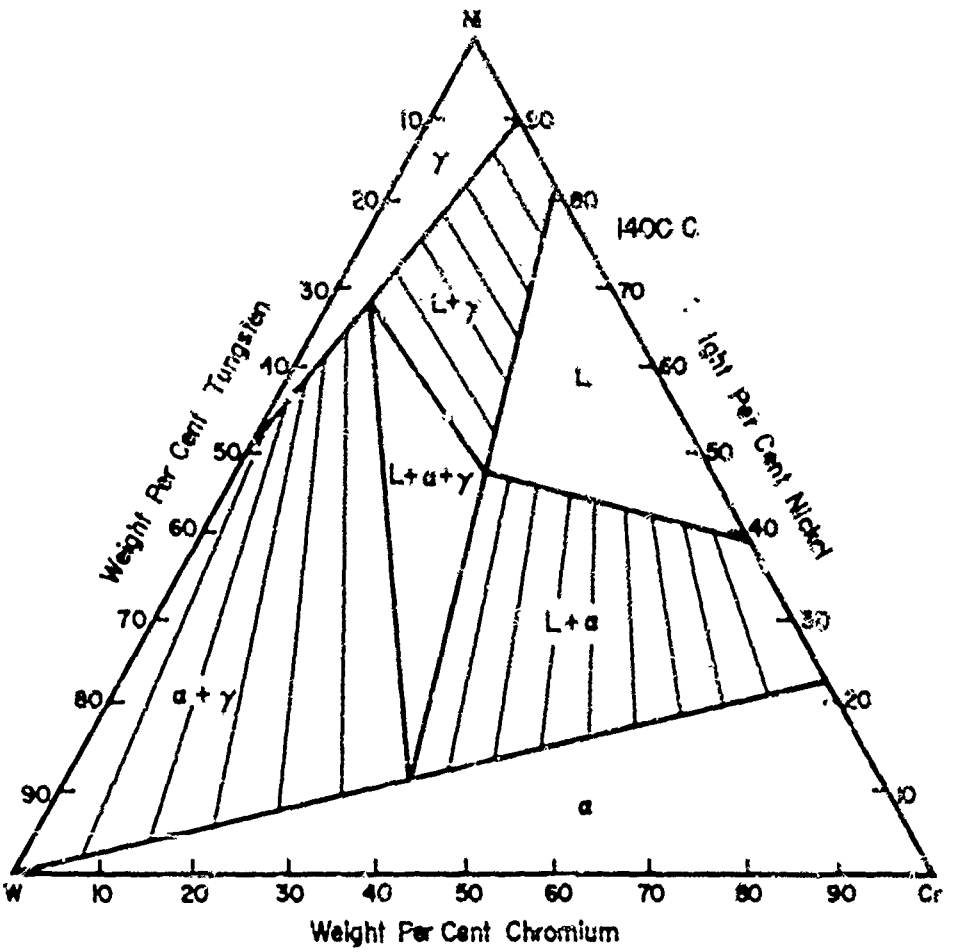


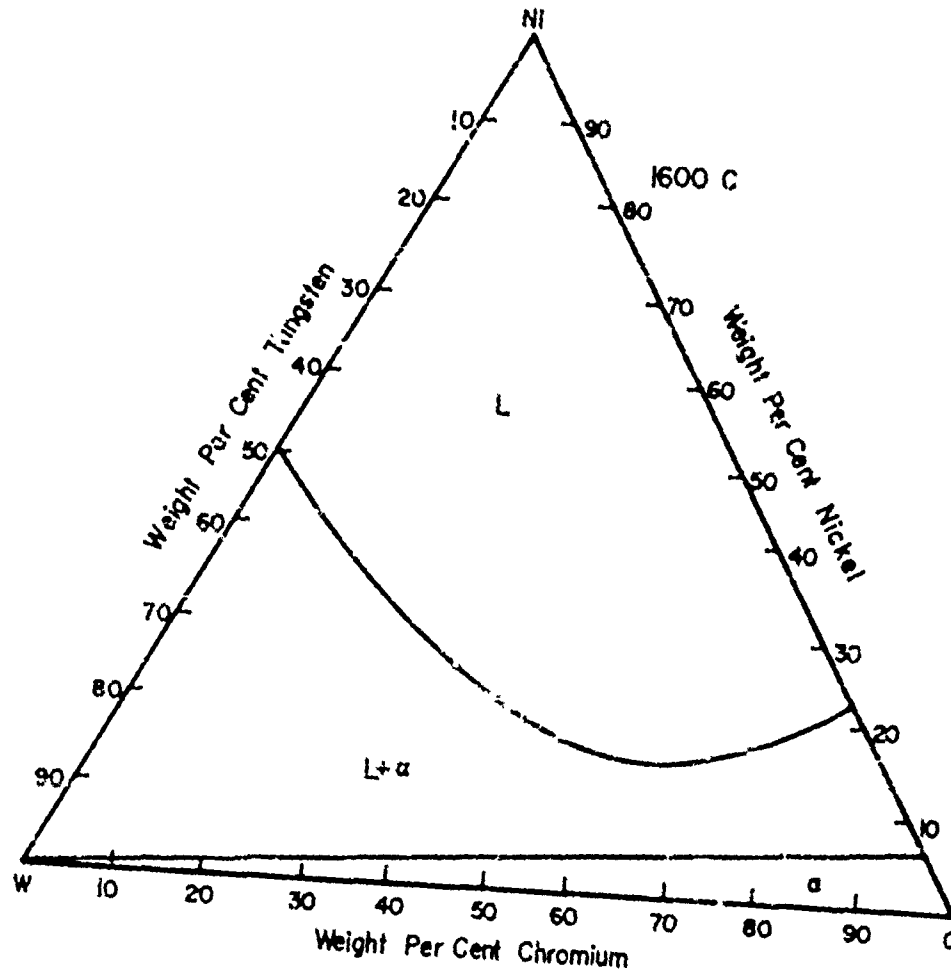
TUNGSTEN-CARBON-TITANIUM SYSTEM[217]



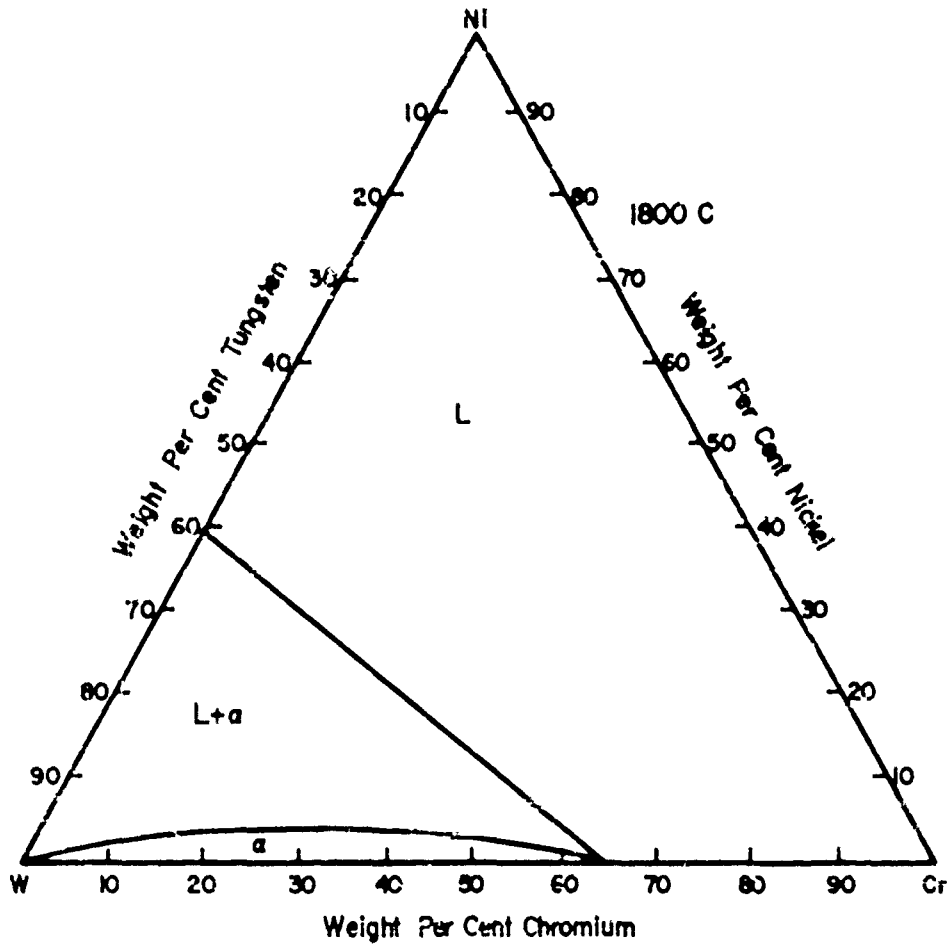

Ni
10
90
20
50
1200 C
γ
30
70
40
60
50
50
60
40
70
30
80
20
90
10
α + γ
α
W
10
20
30
40
50
60
70
80
90
Cr
Weight Per Cent Tungsten
Weight Per Cent Nickel
Weight Per Cent Chromium

TUNGSTEN-CHROMIUM-NICKEL SYSTEM(216)

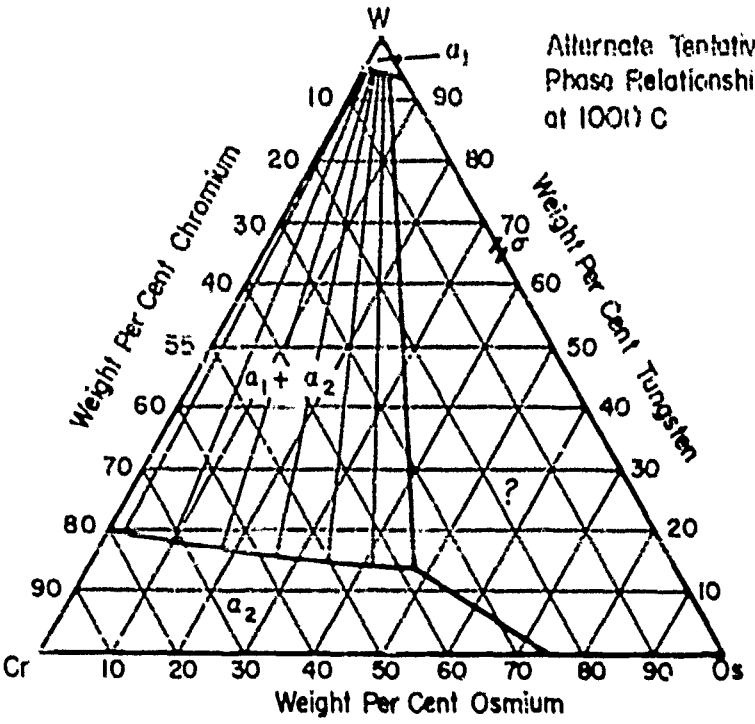


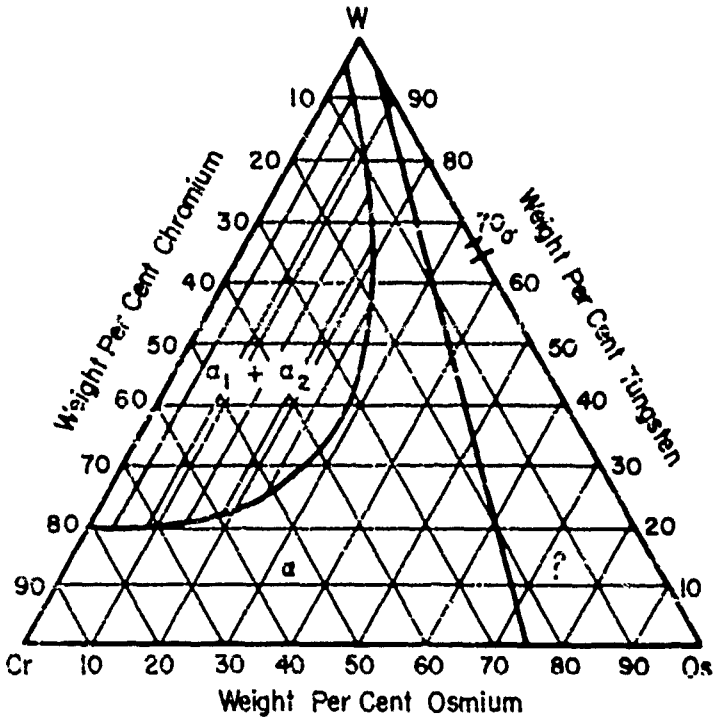

Ni
1600 C
L
L+α
α
W
Cr
Weight Per Cent Tungsten
Weight Per Cent Nickel
Weight Per Cent Chromium
10
20
30
40
50
60
70
80
90

TUNGSTEN-CHROMIUM-NICKEL SYSTEM[216]

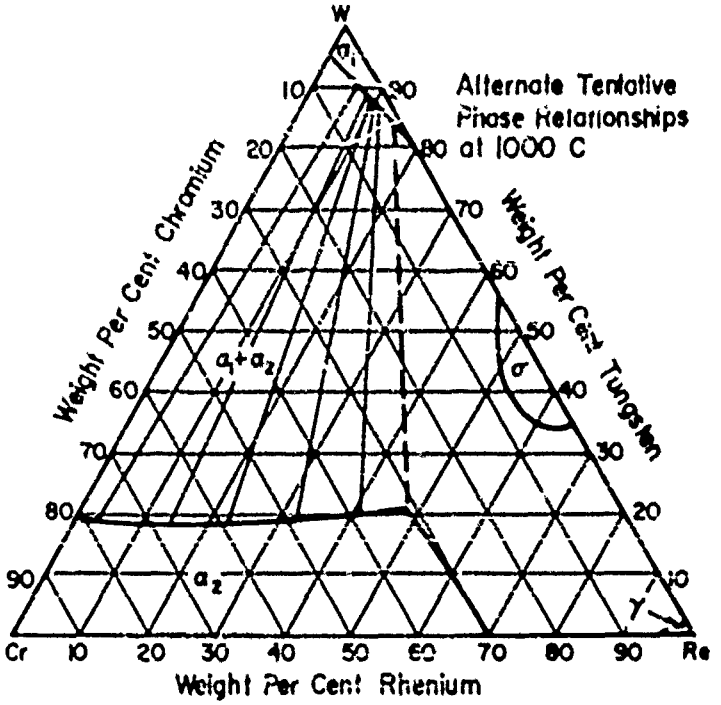


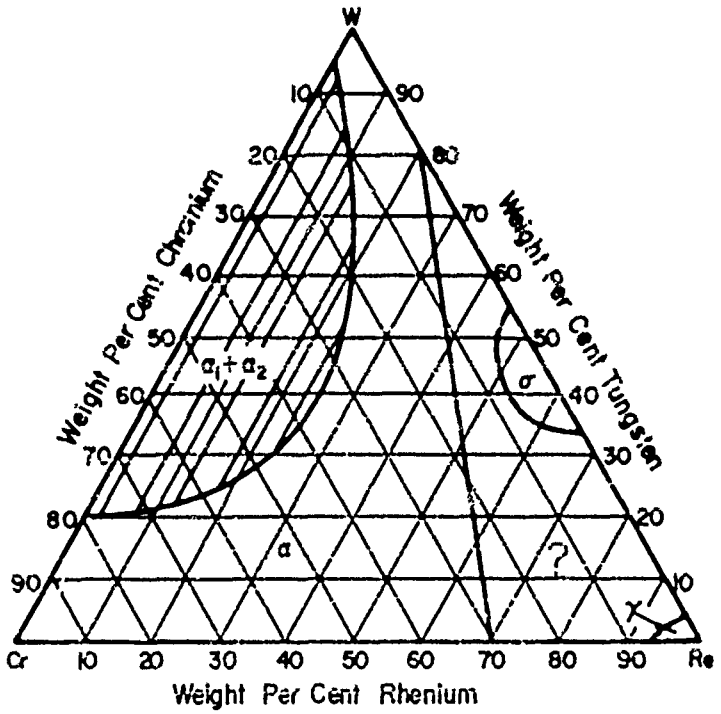
TUNGSTEN-CHROMIUM-OSMIUM SYSTEM[206]



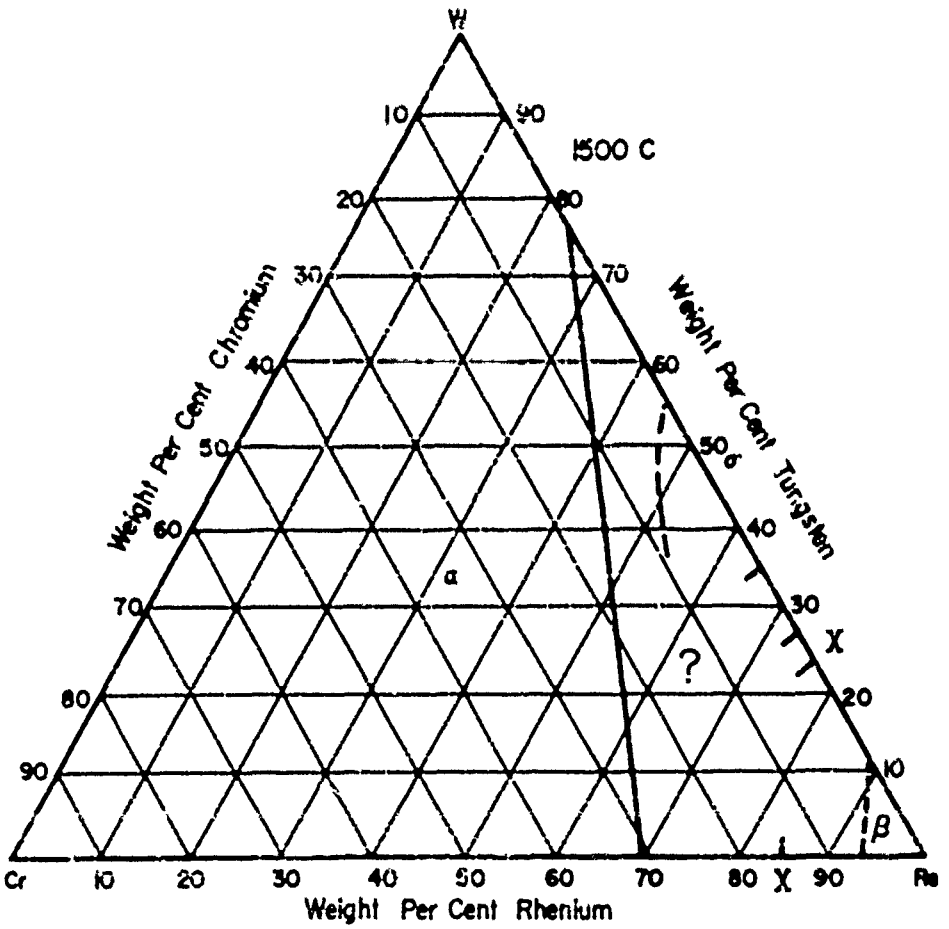


TUNGSTEN-CHROMIUM-RHENIUM SYSTEM(206)

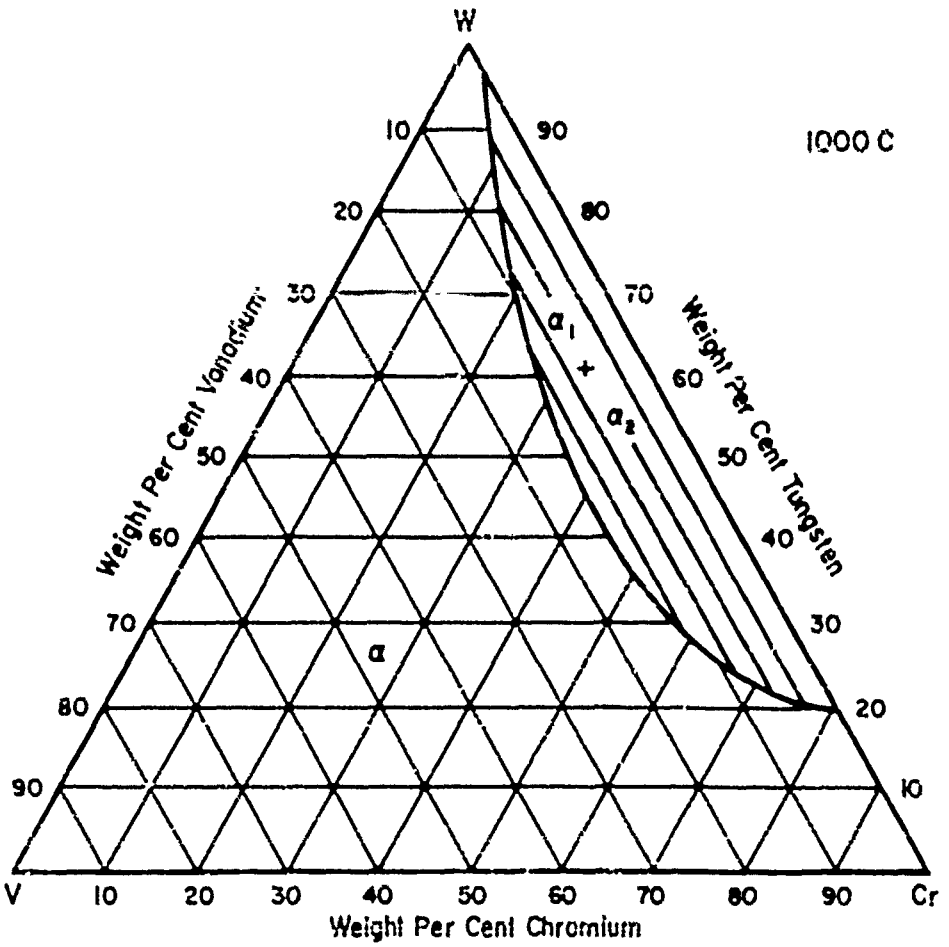




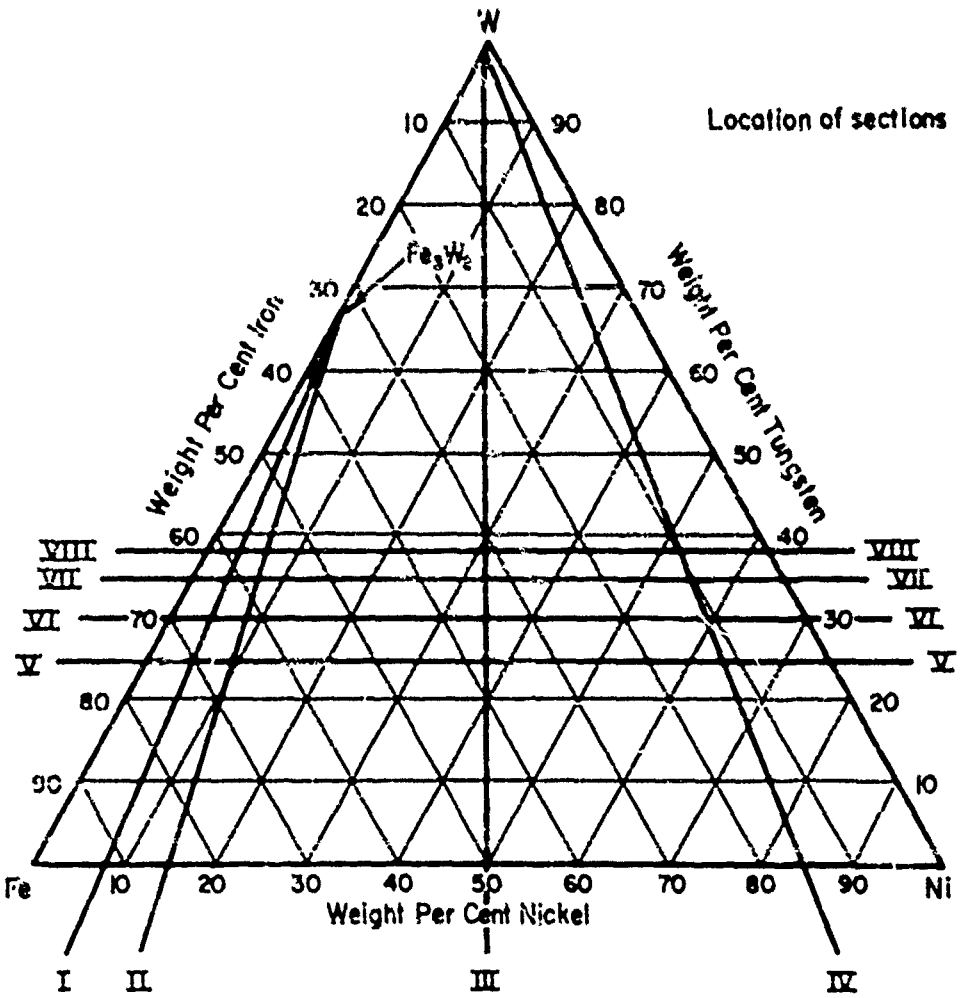
TUNGSTEN-CHROMIUM-RHENIUM SYSTEM(206)



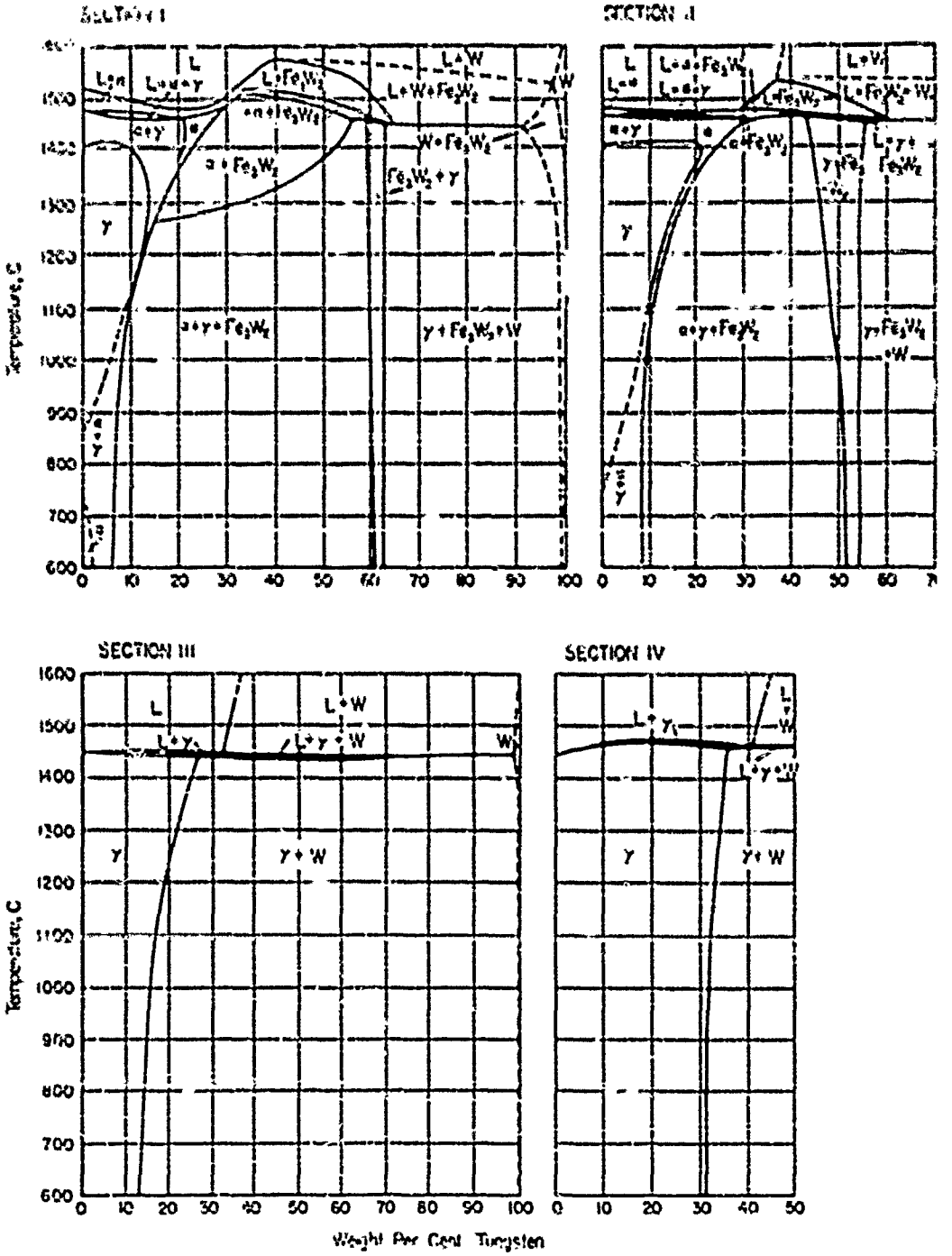
TUNGSTEN-CHROMIUM-VANADIUM SYSTEM[206]



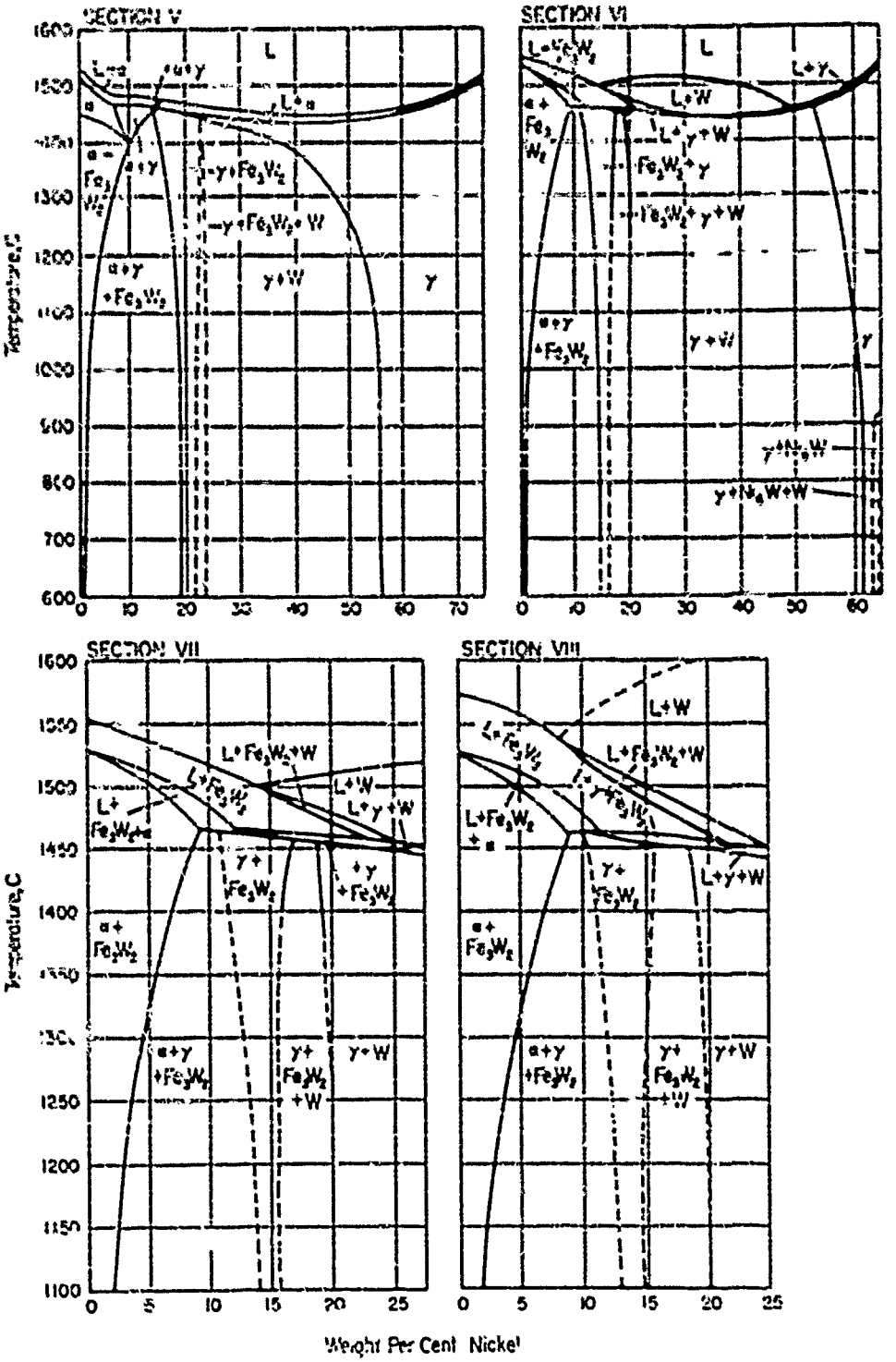
TUNGSTEN-IRON-NICKEL SYSTEM[224]

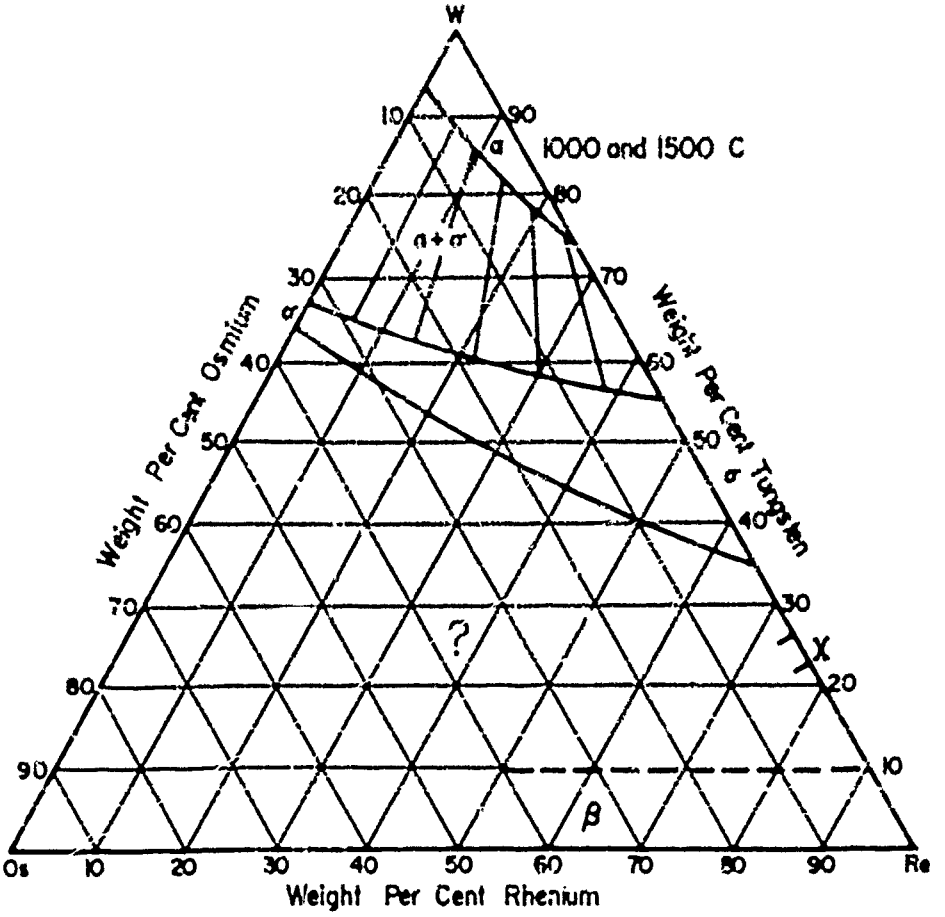


TUNGSTEN-IRON-NICKEL SYSTEM[224]

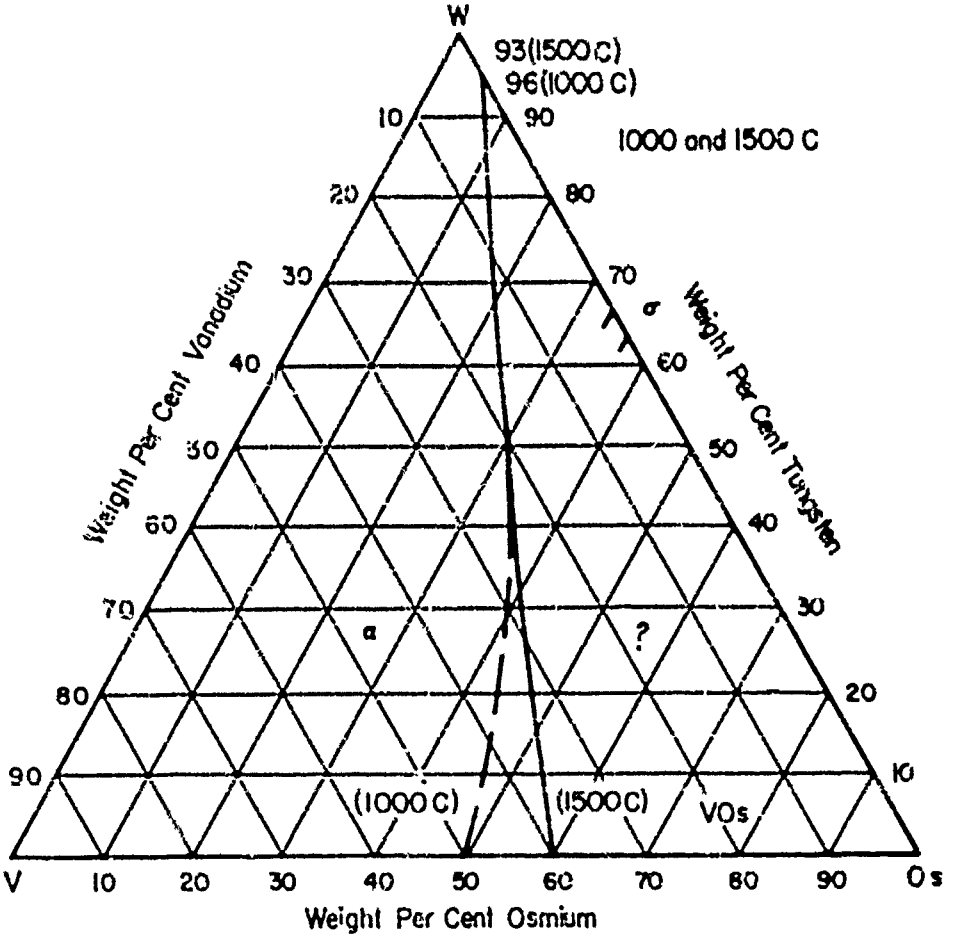


TUNGSTEN-IRON-NICKEL SYSTEM[224]

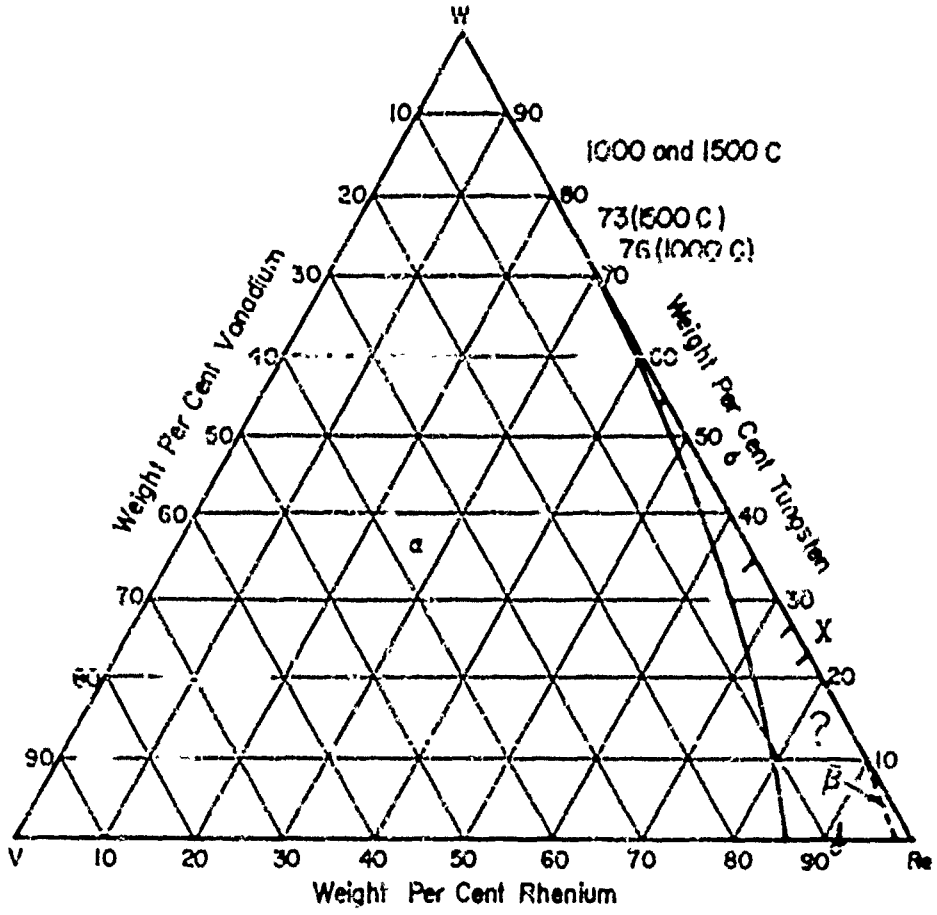



W
1000 and 1500 C
α
α + σ
σ
?
β
χ
Weight Per Cent Osmium
Weight Per Cent Tungsten
Weight Per Cent Rhenium
Os
Re
10
20
30
40
50
60
70
80
90

TUNGSTEN-OSMIUM-VANADIUM SYSTEM[206]



TUNGSTEN-RHENIUM-VANADIUM SYSTEM[206]



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